UNIVERSITY OF CAPE TOWN

STABILITY OF DISTRIBUTION NETWORKS CONNECTED WITH DISTRIBUTED GENERATION

By

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR A MASTER OF SCIENCE DEGREE IN ELECTRICAL ENGINEERING

AUGUST 2002

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DECLARATION

I, Sicelo Mabuza hereby declare that the work contained in this thesis is my own work. All information obtained from reference material has been properly acknowledged. I would like to break down other work done in this thesis:

STABILITY SIMULATIONS

All simulations and analysis carried out in this thesis was conducted by myself without the help of anyone. Guidance was however provided by Prof. CT Gaunt.

CONCLUSIONS

The conclusions are based on my own understanding of the literature and results of the stability studies conducted.

Signature: Signed by candidate
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Date: 10/09/02

This is one is for you Bo Mshengu Mshabalala

ACKNOWLEDGEMENTS

Firstly, I would like to give praise to God almighty for giving me the strength and intelligence throughout my academic career, and if it were not for his grace I would not have reached this stage.

My deepest gratitude is due to my MSc. Supervisor Prof. C. T. Gaunt for the guidance, support and supervision throughout the duration of the MSc. project.

Special thanks is given to my Sponsor, Tibiyo TakaNgwane, for giving me the opportunity to pursue my childhood dream, and understanding my problems when I needed them to.

I would like to thank Prof. N Jenkins as well as Trevor Dudley for their assistance as well as advice while I was conducting a literature survey on this project in UMIST.

Special thanks also go out to the Power-engineering group of the University of Cape Town included, Mbulelo Jojozi, Sengiphile Simelane, Lameka Amuanyena, Ben Sebitosi, Gordon Webber, Caxton Magozore, and Chris Wozniak. Thanks for everything.

Heartful thanks is given to Zwambi Ndhlovu, Parents, Grandmother, Sisters, Brother, and Brothers in law for their prayers, love, patience and encouragement.

Sicelo Mabuza

SYNOPSIS

This thesis describes an investigation into the stability of distribution networks that are connected with distributed generators. Due to the restructuring of the electricity industry in the region as well as environmental concerns, distributed generation is bound to increase at a higher rate in the Southern African region in the near future.

Southern Africa, like many other developing regions, is dominated by electrically weak distribution networks that have relatively high impedance lines. These networks suffer extreme voltage fluctuations when a transient disturbance occurs on the network. The distributed generators are connected onto distribution networks that were designed to operate without any generation, but were designed to receive power from the transmission networks. Once distributed generators are connected to distribution networks, a number of technical challenges are presented. One of the technical challenges includes investigating the stability of distribution networks connected with distributed generation. It would be beneficial to know what effect the connection of distributed generators onto distribution networks would have on the system stability. This is because if the connection of distributed generators onto distribution networks increases instability on the network, the quality of supply of that network would be degraded, therefore the connection of distributed generators must be limited or methods of improving the stability must be implemented. It is important to establish the measures that can be taken to make sure that the generators react in a stable manner when subjected to disturbances and to make sure that the local system stability is not compromised.

The first objective of this thesis was to identify the types of generators that are likely to be connected to Southern African distribution networks and investigate their stability. The next objective was to design model distribution networks that would be utilised to highlight key stability issues that are raised when distributed generation is connected to distribution networks. The third objective was to conduct and analyse stability studies on model as well as existing Southern African distribution networks connected with distributed generation, including the assessment of the implications of potential instability such as on the quality of supply. The last objective was to identify various ways of improving the stability of distribution networks that are connected with distributed generation.

In order to accomplish the objectives of this thesis, a hypothesis that would guide the research was stated as: "Distributed generation that is connected to an electrically weak distribution network will not degrade the system stability, but instead improves the general stability of the local distribution network because it increases the strength of the distribution network." An extensive literature review on the thesis topic was then conducted, which included a visit to the University of Manchester Institute of Science and Technology (UMIST) where the author had the opportunity to review the work done by others as well discuss the thesis topic with leading distributed generation researchers. Preparations for conducting stability studies, which included selecting suitable software for conducting the studies and gathering electrical data for the stability studies, were then conducted. Practical results from the Transkei distribution network, an existing Southern African distributed generation site, were then gathered after a visit to the site and these results were compared to the theoretical results that were established from the model stability studies.

The review of work done by others identified transient stability and voltage stability as being the main forms of stability that create problems or issues when distribution networks are connected with distributed generators. Transient instability was identified to be related to distributed generation technologies that utilise synchronous generators due to their loss of synchronism when they lose stability, and voltage instability was identified to be related to distributed generation technologies that utilise induction generators due to their demand of reactive power when they lose stability. Small signal stability was identified not to greatly impact the stability of distribution networks that are connected with distributed generation. Hydro generators and wind generators were found to be the likely types of distributed generators that would be connected to Southern African distribution networks in the future. These technologies were then utilised in the stability studies.

The stability studies were separated into three chapters, which included transient stability studies, voltage stability studies and stability studies of the Transkei distribution network. The stability studies were conducted to investigate various cases of stability, so as to identify limiting factors where distributed generation is connected to weak distribution systems typical of Southern Africa.

The results of the transient stability studies showed that the closer a large disturbance is to a synchronous generator, the shorter the critical fault clearing time, and an increase in load that is being supplied by a DG decreases the critical fault clearing time (CCT) linearly. Also, an increase in synchronous reactance (Xd), transient reactance (X'd), and sub transient reactance (X"d) lowered the CCT, and increasing the inertia constant (H) resulted in an increase in CCT. A high inertia constant (H) and a low transient reactance (X'd) were found to have the highest effect on lowering the CCT, and if a similar rated generator is designed with these parameters it would have a wider diameter and a shorter length with cost implications.

The findings of the voltage stability studies that were conducted indicated that when an induction generator loses its stability it draws large amounts of reactive power, which lowers the voltage stability of the local distribution network. With an increase in numbers of distributed generation that utilise induction generators the voltage stability of that network could possibly be degraded further once a severe large disturbance occurs close to the generators. This could easily lead to voltage collapse on a weak network. Electrically weak distribution networks were found to be very susceptible to voltage instability when they are connected with distributed generators that utilise induction generators. They are susceptible after the occurrence of a large disturbance on the network. The effects of weak networks were clearly visible on the voltage profiles of the network bus bars during the simulation. Weak distribution networks suffered extreme voltage fluctuations during large disturbances, which were accentuated on bus bars connected with loads.

When the theoretical results from the Transkei study were compared to the practical results found in the field, it was found that there was some correlation. The theoretical results revealed that the critical fault clearing times of the hydro generators were in the order of 190msec to 260msec, which is relatively low. Practically it was found that on most occasions when there is a transient disturbance on the system the generators often trip due to instability. This is possibly caused by the low CCT of the generators. There are however methods used on the Transkei network to improve the stability of the network, which include static var compensators (SVC), synchronous condensers and capacitor banks that are used by Eskom on the Transkei network. The Transkei network was found to be highly dependent the SVC for reactive power compensation, and without it during peak hours the network is likely to have voltage stability problems.

Distributed generation has shown that it has the potential of degrading the system stability to which it is connected if the large disturbances are not cleared before the critical fault clearing times of the distributed generators. Even though some distributed generators have independent control of real and reactive power and are able provide voltage support, once severe large disturbances are introduced onto the network the generator contributes fault current to the fault and it is unable to strengthen the network. The instability of a distributed generator is however likely to only occur when a large disturbance occurs on a network, and large disturbances do not occur very often. Therefore the benefits of using distributed generation outweigh the undesirable possibility of instability on the network.

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LIST OF SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS

AC	Alternating current
ACSR	Aluminium conductor steel reinforced
CCT	Critical fault clearing time
CIGRE	The International Conference on Large High Voltage Electric Systems
CHP	Combined heat and power
DC	Direct current
DG	Distributed generation
EPRI	Electric Power Research Institute
ESI	Electricity Supply Industry
FACTS	Flexible AC transmission systems
GRI	Gas research institute
GTO	Gate-turn-off thyristors
ICAD	Individual channel analysis and design
IGBT	Insulated gate bipolar transistors
LTC	Load Tap changer
PFC	Power factor correction
PV	Photovoltaics
PWM	Pulse width modulation
SABRE-Gen	South African Bulk Renewable Energy Generation
SVC	Static Var ompensators
T&D	Transmission and Distribution

SYMBOLS

S	Apparent power
P	Active power
Q	Reactive power
V	voltage
I,i	current
φ	phase angle of voltage and current
R	resistance

X	reactance
Xd, Xq	direct and quadrature axis synchronous reactance
$X'd$, $X'q$	direct and quadrature axis transient reactance
$X''d$, $X''q$	direct and quadrature axis sub-transient reactance
$T'd$, $T'q$	direct and quadrature axis transient time constant
$T''d$, $T''q$	direct and quadrature axis transient time constant
δ	generator rotor angle
r_a	Armature resistance
X_l	Leakage reactance
T_A	Regulator time constant
T	Regulator input filter time constant
K_A	Regulator time constant
V_{Rmax}	Maximum regulator output, starting at full load field voltage
V_{Rmin}	Minimum regulator output, starting at full load field voltage
K_E	Exciter self excitation at full load field voltage
T_E	Exciter time constant
K_F	Regulator stabilising circuit gain
T_s	Regulator stabilising circuit time constant
E_1	Exciter voltage for E1
$S_E(E1)$	Saturation at E1
E_2	Exciter voltage for E2
$S_E(E2)$	Saturation at E1
R_P	Turbine steady state regulation setting or droop
G_{max}	Maximum gate position
G_{min}	Minimum gate position
$Mxgtor$	Maximum gate opening rate
$Mxgtcr$	Minimum gate closing rate
T_P	Pilot valve servomotor time constant
T_g	Main servor time constant
Rt	Temp. Droop

GLOSSARY

Asynchronous generator:	Also referred to as an induction generator. The rotor runs at a slightly faster rotational speed than the stator field
Despatched:	Generating plant that is under central control and so 'despatched' or controlled by the power system operator
Digsilent Power factory:	Integrated power system analysis tool that handles load flow, fault analysis, dynamic simulations and other features
Distributed Generation:	Generation which is connected to the distribution network
Fault level:	The fault level at a given point in a power network is a measure of the fault current that would result from a balanced three phase fault at that point. The fault level is higher for networks that are meshed more heavily meshed and increases as the point considered moves closer to generators
Flicker:	Used to describe high frequency (up to 10Hz) variations in the network voltage magnitude which may give rise to noticeable changes in light intensity or 'flicker' of incandescent lamps
Islanding condition:	Separation of two electrical systems during faults
Networked distribution feeder:	A distribution feeder that is connected to more than one supply point
Photovoltaic:	The physical effect by which light is converted directly into electrical energy
Radial distribution feeder:	A distribution feeder that is connected to one supply point only

Synchronous generator: A generator whose rotor operates in synchronism with its stator field. In its usual construction a synchronous generator allows independent control of real and reactive power.

CHAPTER 1

INTRODUCTION

1.1 INCREASE OF DISTRIBUTED GENERATION

Over the last decade there has been an increasing international interest in the introduction of small and medium sized generators to distribution networks. The small and medium sized generators are referred to as distributed generation (DG), and also referred to as embedded or dispersed generation because the generators are embedded within the distribution network. Southern Africa has experienced a steady increase in the number of small generation sites. This includes a wind farm, standby generators, hydro-generators, photovoltaic sites in rural areas and other generating plants. It is expected that, due to the restructuring of the electricity industry in the region as well as environmental concerns, distributed generation sites will increase at a higher rate in the near future. The key factors that will result in an increase of DG in the Southern African region are [16]:

- Technological development which has increased the efficiency and reduced the cost per kW of small generating units to challenge the capital and operating efficiency of central generating stations
- Environmental assessment of various energy sources, and concerns over the emissions that some release into the atmosphere
- Control systems (including FACTS devices) have become more advanced and cheaper, therefore it is easier to operate small generators in parallel with the grid
- The need for network voltage support in many weak distribution networks in Southern Africa

Before one continues any further, the definition of DG needs to be clearly understood. DG is not necessarily characterised by the size or type of generating plant even though that is often the case. Most importantly, DG is characterised by its location and the mode of operation. DG is located in the distribution network or on the customer side of the meter, and is not centrally (Nationally) dispatched. In Southern Africa the distribution network is defined to be a network that operates at a voltage level below and including 132kV. Chapter 2 defines and discusses distributed generation at a greater length.

1.2 DISTRIBUTION SYSTEM COMPLEXITY INCREASED BY DG

Electricity utilities are used to operating distribution networks with large amounts of power flowing from the transmission networks and distributed at a distribution level (less than 132kV) to customers. The behaviour of conventional distribution networks is well understood, and the power flows are predictable. Voltage control and system protection are carried out based on the flow of current in one direction. With the location of DG on distribution networks operating in parallel with distribution networks, the networks become multiple source feeders. The power flows in feeders become more and more unpredictable.[10] This is because with significant penetration of embedded generation the power flows may become reversed and the distribution network is no longer a circuit supplying loads but an active system with power flows and voltages determined by the generation as well as the loads [25]. It is imperative to verify that the installation of distributed generation on distribution systems in the Southern African region will not compromise local system stability and that the generator will react in a stable manner to transients and other disturbances in the power system. This is because the instability of the distributed generators would possibly affect the quality of supply of the distribution network.

The stability of an electrical network is influenced by many factors and is not a simple area of study. The stability of distribution networks that are connected with DG is also not a simple operation and is complicated by the following factors;

- Power system stability has previously been investigated and studied intensively at transmission levels, but much less at a distribution level, therefore conducting stability studies on distribution networks is a relatively new area of study.
- Distributed generation plant includes different types of technologies that utilise different conventional electrical machines and power electronic circuits, and these generation plants have different modes of operation and characteristics.
- The methods of control that are utilised by the distributed generators are different, and the actions of these controllers can influence the stability of the distribution network.
- Electrical networks are unique because they have a variety of different layouts and characteristics.
- The distribution systems in Southern Africa are relatively weak, especially compared with western countries where most distributed generation is installed and most research has been carried out.

1.3 PROBLEM STATEMENT

Southern African distribution networks presently have a few distributed generation plants connected to them. Due to the increased interest in distributed generation worldwide, distributed generation will probably increase at a higher rate in the Southern African region in the near future. Modern distribution networks were designed to operate without any generation on the distribution network or at customer loads. When distribution networks that were designed to operate without any generation are connected with generators, a number of technical and regulatory challenges are presented. One of the technical challenges includes investigating the stability of distribution networks that are connected with distributed generation. It would beneficial to know what effect the connection of distributed generation onto distribution networks would have on the system stability. This is because if the connection of the distributed generators on the distribution network increases instability of the network, the quality of supply of that network would be degraded therefore the connection of DG units must be limited. And if the connection of the distributed generators onto the distribution network increases the stability of the network, the connection of DG units must be encouraged. This investigation will assist distribution network planners, when planning for future distribution networks.

Given the challenge at hand, a hypothesis that will guide the research so that a constructive investigation on the stability of distribution networks connected with DG is conducted is as follows;

"Distributed generation that is connected to a weak distribution network will not degrade the system stability, but instead improves the general stability of the local distribution network because it increases the strength of the distribution network."

The problem that needs to be addressed includes investigating the general stability of distribution networks that are connected with distributed generators, so that one can predict the crucial factors that influence the stability of distribution networks given a typical South African distribution network. This includes investigating all forms of stability but concentrating on the more critical forms of stability. In order to do this, it is necessary to define distributed generation, identify the types of generators that are likely to be connected to distribution networks and how they impact the stability of distribution networks, identify the different applications of distributed generation, determine the impact of distributed generation connected to a distribution network and identify the key stability issues that are raised by the connection of distributed generation onto distribution networks.

1.4 OBJECTIVES OF RESEARCH

The objectives of this research are to increase the understanding of the stability of distributed generation connected to the distribution system by:

- Identifying the types of generators likely to be connected to the Southern African distribution networks.
- Designing non-actual (model) networks that would be utilised to identify key stability issues that are raised when distributed generation is connected to a distribution network.
- Conducting and analysing stability studies on model as well as existing Southern African distribution networks connected with distributed generation, in order to consolidate the understanding of this phenomena.
- Assessing the implications of potential instability, such as on the quality of supply.
- Identifying various ways of improving the stability of distribution networks that are connected with distributed generation

This research seeks to investigate the general stability of distribution networks that are connected with distributed generation. All forms of stability will be investigated including transient stability, voltage stability and small signal stability. Stability studies will be carried out on model (non-existing) distribution networks that can be typically found in the Southern African region, as well as existing distribution networks from South Africa and Swaziland. The studies will be carried out on non-existing as well as existing networks in order to investigate key stability issues that are raised when DG is connected to distribution networks, and to investigate the general stability of different combinations of distributed generation plant together with different network topologies and parameters.

1.5 RESEARCH METHODOLOGY

The research methodology that the author undertook was in the following order:

- An extensive literature review was conducted in the initial stages of the research. The literature survey was however dominated by technical papers because only a few books have been published on the distributed generation subject. The literature review established previous work that has been done on the topic, and enlightened the author on general aspects of distributed generation. A visit to the University of Manchester Institute of Science and Technology (UMIST) was also carried out as part of a review of previous work done. The visit exposed the author to other distributed generation researchers and provided the opportunity to discuss matters that raise concern. Some of the researchers that were met included Nick Jenkins, Goran Strbac and Ron Allan who wrote a book on Embedded Generation [26].

- The second stage of the research included investigating and gathering different information on power system simulation software that would be suitable for carrying out stability studies for the research. The most suitable software in terms of price, functionality and technical support was purchased.

- The subsequent stage involved gathering electrical data for generators and networks for the different case studies and different investigations. This included gathering information from Swaziland and the Eastern Cape that have a number of hydro generation plants connected at a distribution voltage level.

- The next stage included carrying out stability studies and simulations on different case studies. The stability studies conducted were mainly transient stability and voltage stability. The stability studies were conducted on model systems as well as existing distribution networks that are connected with DG in the Southern African region.

- A comparison of theory results with practical results was then carried out. Practical results were acquired after a visit to the Transkei distribution network that has four hydro DG power stations connected to it. The visit included a tour to the hydro power stations, Zimbane substation and the East London regional control centre.

- General conclusions were drawn after the analysis of results.

1.6 CHAPTER OUTLINE

This report consists of nine chapters, arranged as follows:

Chapter 1 introduces the topic of the stability of distribution networks that are connected with DG, and starts off by giving a background and rationale of the topic. It carries on to present the problem statement, and the hypothesis that guides the research so that a constructive investigation is conducted. The objectives of the research are then outlined, and lastly the research methodology is described.

Chapter 2 is a review of previous work that is relevant to the research that has been published over the past decade. The main aim of this chapter is to unify the information and concepts in order to form a theoretical basis for the subsequent analysis. It describes why the study is confined to rotating machines, not including power electronic connected systems.

Chapter 3 presents the functional details of the distributed generators to be used in the stability studies. It covers the different conventional machines that are utilised by distributed generation, and carries on to present hydro power plants and wind power plants.

Chapter 4 covers concepts and definitions of power system stability. It carries on to present classical stability analysis methods and the stability analysis of distribution networks with DG. The chapter continues to discuss the stability issues that are raised by distributed generators, and describes the stability properties of conventional machines. It also describes briefly the power system software used in the stability studies that follow in chapters 5,6 and 7.

Chapter 5 and 6 presents transient and voltage stability studies respectively conducted to increase the understanding of transient and voltage stability of model distribution networks connected with DG. Each chapter describes two case studies.

Chapter 7 presents a stability study of the existing Transkei distribution network. This chapter compares theory results together with practical results, which differentiates it from the case studies in previous chapters.

Chapter 8 highlights the different implications of potential instability on a distribution network that is connected with DG, such as on the quality of supply.

Chapter 9 evaluates the material covered by the thesis and reviews the validity of the initial hypothesis. The chapter also identifies possible topics for further research.

CHAPTER 2

REVIEW OF PREVIOUS WORK

Stability studies on distribution networks are an area of study that has not been covered extensively in the past. Traditionally, stability studies have been carried out on transmission networks because they are connected with generators. However with the introduction of generators onto distribution networks, stability studies have to be carried out on distribution networks. This chapter tries to identify existing knowledge related to the stability problems of distribution networks connected with distributed generation.

This chapter is divided into nine sections. The first section deals with the distributed generation topic, where the definition of distributed generation (DG) is presented and the position of DG in the electricity industry is discussed. The second section considers the various DG technologies that can be connected to a distribution network and briefly discusses their stability aspects. The next section discusses the different applications of DG. The fourth section presents the impact of DG connected to a distribution system, by focussing on different power quality issues and operational issues. The fifth section identifies the problems that can be encountered when DG is connected to a distribution network. The sixth section reviews the different forms of stability and establishes whether they are worth being investigated. The next section covers the outcome of a visit to the University of Manchester Institute of Science and Technology (UMIST) that was undertaken to review the work of other distributed generation researchers. The eighth section presents distributed generation in Southern Africa, and establishes present existence of DG in Southern Africa as well as the future scope of DG in Southern Africa. Lastly a summary of the key findings of the chapter is presented.

2.1 DISTRIBUTED GENERATION

Before investigating the stability of distribution networks that are connected with DG it is important to define the scope of distributed generation in order set the context for this research. This section reviews a definition that is applicable in Southern Africa and continues to review the utility structure in Southern Africa and the increasing system capacity needs.

2.1.1 DISTRIBUTED GENERATION DEFINITION

Current literature does not use a consistent definition of distributed generation. This is because different countries and different institutions have their own definition of DG. However there has been an attempt to provide a consistent globally applicable definition of DG that could be applied in both traditional vertically integrated utility environments and newer competitive electricity markets by Ackermann [1]. CIGRE working group 37.23 [5] also attempted to provide a globally applicable definition, however this definition has differences with the Ackermann [1] definition. A distributed generation research group [16] from the University of Cape Town therefore proposed a definition that would be applicable in the Southern African context. This definition would be used to set the context for further distributed generation reports.

The different aspects that are significant in the derivation of the DG definition include; Interconnection voltage level, mode of operation, location, capacity, technology, ownership & planning and the power delivery area.

One of the contentious aspects includes the capacity of the generator. The capacity of a generator is an important aspect when considering stability because low capacity generators respond differently to high capacity generators. The following different capacity definitions are currently used [1]:

- The Electric Power Research Institute (EPRI) defines distributed generation as generation from 'a few kilowatts up to 50 MW'
- According to the Gas Research Institute (GRI), distributed generation is 'typically between 25 kW and 25 MW
- Preston and Rastler define the size as 'ranging from a few kilowatts to over 100 MW'
- Cardell defines distributed generation as generation 'between 500kW and 1 MW'
- The International Conference on Large High Voltage Electric Systems (CIGRE) defines DG as 'smaller than 50 -100 MW'

Another aspect that is significant in the derivation of the DG definition includes the mode of operation of the distributed generator. According to Jenkins [26] distributed generators are not subject to central dispatch by the national control. Depending on the size and agreements of the generating plant, some generating units may be dispatched by national control. These DG plants would therefore react to the national electricity demand. The DG units that are not dispatched may however respond to changes in tariff prices. Nevertheless, the majority of distributed generators operate independently of the loading and voltage conditions on the local network.

The different distributed generation definitions by Ackermann [1] and the CIGRE [5] working group were respectively defined as:

- "Distributed generation is an electric power source connected directly to the distribution network or on the customer side of the meter."
- "Distributed generation is any generation that is: [i] not centrally planned, [ii] not centrally dispatched, [iii] usually connected to the distribution network, and [iv] smaller than 50-100MW."

In the Southern African context, it was felt that a definition that draws aspects from each of the above characteristics would be appropriate. The definition for the Southern African context was therefore proposed to being [16]:

Distributed generation is any source of electric power that is interconnected with an electricity supply network at a system voltage level not exceeding 132kV. The generator is not centrally dispatched. It is not a trading participant in a power pool but usually responds to a tariff signal.

Distributed generators were defined not to operate as centrally dispatched because it was felt that the practice of centrally dispatching a generator aligns its application more with the traditional generation ideology than with the intrinsic uncertainty that is characteristic of not centrally dispersed "dispersed" units. [16]

Where the ownership of a generator is likely to have an impact upon its operation, the distinction must be made between utility-owned and independently-owned DG. Distinction can also be drawn between distributed generators of different capacity classes. The following subcategories of DG were recommended:

Classification	Generator Capacity
Micro DG	0-50kW
Small DG	50kW-500kW
Medium DG	500kW-5MW
Large DG	5MW-50MW
Very Large DG	Above 50MW

Table 2.1: Sub-classification of DG for use in South Africa [16]

This definition will be used to verify whether the generators connected to existing networks are indeed distributed generators, and typical examples in Southern Africa. The definition will also be used to set the context for further distributed generation reports.

2.1.2 UTILITY RESTRUCTURING

The government of South Africa has indicated its commitment to restructuring the electricity industry of South Africa, in line with recent world trends in de-regulation. At a media briefing on 10 August 2000, the Minister for Public Enterprises unveiled the government's policy framework for Government's accelerated programme for restructuring of state owned enterprises. With regard to generation, the minister said [12]:

> "We are evaluating different models for restructuring Eskom. In line with the principles of restructuring, it has been agreed the competition in generation is necessary. Initially different independent generating companies will be formed to promote internal competition. This will result in greater market efficiencies. The most appropriate model is still to be evaluated."

From the Minister's speech it is clear that South Africa is heading towards restructuring that would open up the South African electricity industry. Governments from other countries in the Southern African region will also be pressured to restructure their electricity industry. When the electricity industry of the Southern African region is restructured, distributed generation would therefore have an opportunity to increase in numbers. To a certain extent this explains the current existence of DG in Southern Africa.

2.1.3 INCREASING SYSTEM CAPACITY NEEDS

Electrical demand in Southern Africa is estimated to be growing at a high rate, due to the population explosion as well as economic growth. With time this will be a problem because the generating capacity as well as other system capacities will not match the demand. Distributed generation offers an alternative to the central plant model, and relieves transmission constraints. Instead of upgrading distribution networks when power demand increases, distributed generation would offer a cheaper alternative. With the penetration of DG onto distribution networks stability studies have to be conducted to ensure that the introduction of DG does not compromise the stability of the distribution network.

2.2 ELECTRICAL MACHINERY USED BY DISTRIBUTED GENERATORS

The types of electrical machinery used by distributed generators include synchronous machines, induction machines and power electronic devices. Some DG technologies have the capability of utilising any conventional electrical machinery however this is influenced by the design of the DG plant as well as its application. Whereas some DG technologies are restricted to one type of electrical machinery due to the manner in which they generate electricity. Sen and Nelson [47] confirm that induction generators are favoured to the other types of electrical machinery due to their simplicity and lower cost. The stability properties of the various electrical machinery differ. The following table by Sen and Nelson [47] compares induction generators and synchronous generators;

Induction generators	Synchronous generators
No excitation system (field winding, exciters, AVR, etc.) needed if connected to utility system	Requires separate dc power supply for excitation, and extensive excitation control system including exciters, voltage regulators etc.
Squirrel cage rotor (simple design, rugged construction)	Rotor has wound field poles
Needs no synchronisation equipment for connection to the system	Must have synchronising controls
Will not supply sustained current to a system short circuit since the excitation flux will quickly become zero	Will feed sustained current to a system short circuit
Power factor not fixed but varies with load. The generator can deliver only leading current.	Power factor can be controlled easily by changing the field current or excitation voltage
Doesn't have a definite speed, speed is higher than the synchronous speed, increased load requires higher speed	Output frequency set by prime mover speed. Machine runs at synchronous speed
Efficiency lower than the comparable rated synchronous machine	Higher efficiency, may reach 96% in large sizes
Protective relaying needs only simple controls	In general, complicated protection and control scheme
Cannot operate as an isolated power source unless magnetising current is supplied by external capacitors	Can operate as an isolated power source
Frequency and voltage controlled by connected utility system regardless of speed	
Lower first cost and maintenance cost	

Table 2.2: Comparison of induction and synchronous generators [47]

Power electronic inverters are different from synchronous and induction machines because they are not rotating machines but instead utilise semi-conductors. Power electronics do not require additional control devices such as exciters and governors. Their ability to utilise pulse width modulation (PWM) or rapid switching electronics assists them in controlling the amount of voltage, power factor, active power and reactive power they introduce into a connected distribution network.

2.2.1 SYNCHRONOUS GENERATORS

Synchronous generators are extensively used for distributed generation because they allow independent control of real and reactive power. However they have to be carefully synchronised with the network before connection and this requires both synchronising relays and precise control over the speed of the generator.

Synchronous generators operate over a wide range of real and reactive powers and the reactive power can be controlled independently of the real power. According to Jenkins [24], a small generator connected to a distribution system has little control over its terminal voltage and none over the system frequency. Its excitation system determines the reactive power flow, and the governor is used to control the real power output of the unit.

The definition of Transient stability by Kundur [31] states that, "Transient stability is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance," it is noted that only synchronous generators maintain synchronism with the network. This definition therefore associates transient stability with synchronous generators and not induction generators. Redfern and Checksfield [43] together with Jenkins et al [26], identified that transient disturbances are a threat to the stability of DG units that utilise synchronous generators because they can result in generator pole slipping. If a power system disturbance persists beyond a certain length of time, the synchronous generator will inevitably swing out of synchronism. When the distributed generator swings out of synchronism it pole slips with respect to the main supply of the distribution network. The pole slipping is accompanied by dramatic fluctuations in the currents absorbed and provided by the distributed generator.

2.2.2 INDUCTION GENERATORS

Sen and Nelson [47] generalise by saying, Induction generators are attractive for distributed generation because of the simplicity of their construction, the lack of synchronising and the damping they introduce into the drive train of the generating set. Induction generators are not able to contribute reactive power into the grid. Instead they require reactive power in order to operate. During large disturbances induction generators draw large amounts of reactive power, which according to Akhmatov et al [2] can jeopardise the voltage stability of the connected network. Jenkins et al [26] agree with Akhmatov et al [2] by stating that voltage stability is associated with induction generators due to the large reactive power they draw during large disturbances.

When an induction generator is connected to the network high transient current will flow. There will always be a large, very fast, magnetic inrush current transient similar to that which occurs when a transformer is energised. Also, depending on the rotor speed there may be a slower transient as the generator is pulled towards its operating slip. Both transients may be controlled using anti-parallel thyristor soft-start units, shown in Figure 2.1. These devices operate by controlling the firing angle of the thyristors so building up the flux in the generator slowly and then limiting the current that is required to accelerate the drive train. [26]

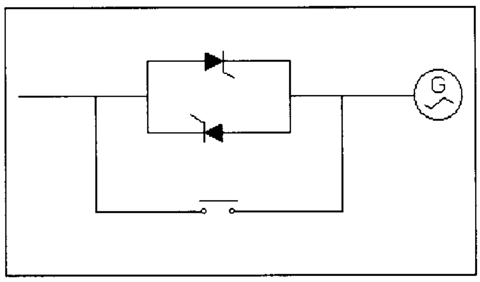


Figure 2.1: Soft-start unit for induction generator (only one phase shown) [26]

2.2.3 POWER ELECTRONIC INVERTERS / CONVERTERS

Power electronic devices are used in various configurations to interface embedded generators with the distribution network. The main advantage of this setup is that the speed of the generator is no longer linked to the network frequency. Another advantage is that power sources of direct current that include, photovoltaics, fuel cells and batteries, require such an interface to convert the power into AC. [26]

Conventional power electronic inverters use thyristors as switching devices. However this arrangement is limited by the fact that the power factor of the network side converter, which is proportional to the DC link voltage, has to be kept low on weak networks. It also injects significant harmonic currents into the network therefore filtering is required. The more recent power electronic converter is the voltage source forced commutated converter. This power electronic device uses either insulated gate bipolar transistors (IGBTs) or gate-turn-off thyristors (GTOs) as switches. It can run at any desired power factor using fast switching in a PWM pattern, and does not produce low order harmonics. [26]

Power electronic inverters have the capability of controlling the amount of active and reactive power. And because voltage stability is mainly a problem of maintaining the amount or reactive power in a system, power electronic inverters have a big role to play in improving the voltage stability of weak distribution networks. However due to the present high costs of power electronic inverters/converters are presently not economical.

2.3 DISTRIBUTED GENERATION TECHNOLOGIES

A wide range of technologies fall under the category of distributed generation. These technologies include photovoltaics (PV), wind turbines, fuel cells, biomass, gas turbines, hydro turbines, reciprocating engines, and batteries. The different technologies operate under different conditions, and utilise different conventional electrical machinery. Distributed generation technologies either utilise synchronous generators, induction generators or power electronic inverters to generate electricity into the distribution network. In this section the different technologies will be discussed, and the focus will be on factors or parameters that are relevant to the stability of these technologies. But firstly, Table 2.3 summarises the key specifications of some technologies. [19]

	Recip Eng: Diesel	Recip Eng: Natural gas	Micro Turbine	Combust gas turbine	Fuel Cell	Wind Turbine	Photo-voltaic	Hydro power plants
Size	30kW-6MW	30kW-6MW	30-400kW	0.5-30MW	100kW-3MW	10kW-3MW	1KW-1MW	0.5- over 50MW
Installed cost ($/kW)[1]	600-1000	700-1200	1200-1700	400-900	3000-4000	1000	6600	800-2000
Electrical Efficiency	32-38%	27-34%	25-30%	21-40%	36-50%	25%	6-19%	Over 35%
Cost of Energy ($/kWh)	0.005-0.015	0.007-0.020	0.004-0.01	0.003-0.008	0.0019-0.0153	0.01	0.0017	> 0.01

[1]Cost varies significantly based on siting and interconnection requirements, as well as unit size and configuration.
#The hydro power plant specifications were estimated

Table 2.3: Distributed generation technologies installed costs, electrical efficiency and cost of energy [19],[26]

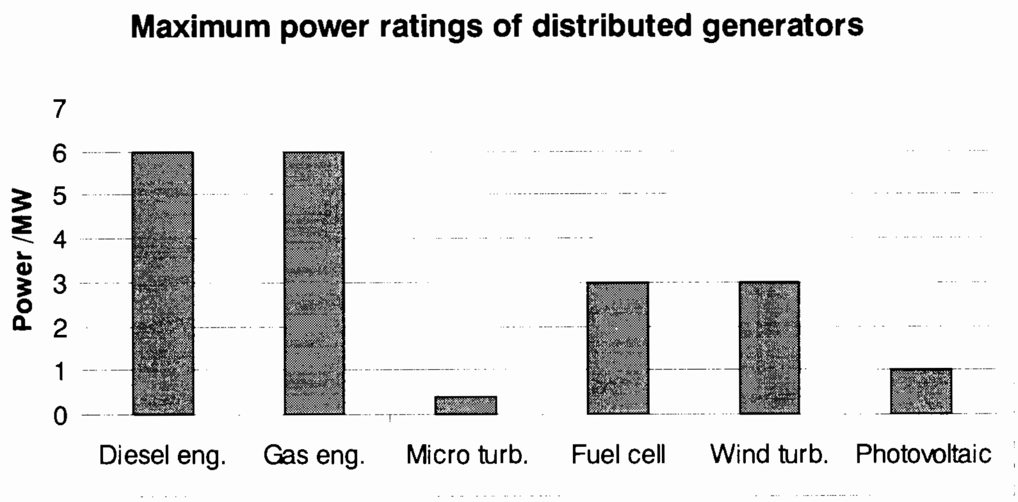


Figure 2.2: Maximum power ratings of distributed generation technologies

Table 2.3 and Figure 2.2 show that the general size of distributed generators that were looked at is relatively small when compared to the centralised large generators. The installation cost ranges from $400 to $4000 per kW, which has dropped significantly since some of the technologies were first introduced. Photovoltaics are the most inefficient technologies with an electrical efficiency ranging from 6-19%, and fuel cells are the most efficient of the technologies that have been looked at with an electrical efficiency ranging from 36-50% but they also happen to be the most expensive.

2.3.1 RECIPROCATING ENGINES

Reciprocating engines can either be diesel or natural gas engines. According to Johnson [36], they were amongst the first distributed generators to be developed, 100 years ago. The power generators can range from small portable gen-sets to engines the size of a house, with a power rating of several megawatts. Compression ignition engines can operate on diesel fuel or heavy oil, or they can be set up in a dual-fuel configuration that burns primarily natural gas with a small amount of diesel pilot fuel and can be switched to 100% diesel. Spark ignition engines for power-generation use natural gas as the preferred fuel, however they can be set up to run on propane or gasoline. [36]

Reciprocating engines are grouped into three classes. Slow motors (<300rpm, up to 50MW), Semi-fast motors, (300-750 rpm, up to 20MW) and fast motors, (750-1800rpm, 1-5MW). Heavy fuel is used in the slow and semi-fast motors, light fuel as well as natural gas is used in the fast motors. The efficiencies of reciprocating engines range from 27-34% for natural gas engines, and

32-38 for dual fuel engines. The waste heat from these engines is often captured and used for other applications, just like cogeneration schemes. [5]

Smaller engines are often designed for transportation and can be converted to power generation with little modification. Larger engines are mostly designed for power generation, mechanical drive, or marine propulsion. Almost all engines that are used for power generation are four strokes and operate in four cycles (intake, compression, combustion, and exhaust). [19]

Reciprocating engines are likely to be made of synchronous machines. Reciprocating engines would therefore be under the threat of trying to maintain transient stability after the occurrence of a nearby large disturbance. The stability of reciprocating engines would be influenced by the electrical parameters of the synchronous generator and the controls it utilises.

2.3.2 MICRO-TURBINES

Micro-turbines have a power rating range of approximately 30kW to 200kW, and are combustion turbines. The basic technology used in micro-turbines is derived from aircraft auxiliary power systems, diesel engine turbochargers, and automotive designs. Micro-turbines consist of a compressor, combustor, turbine, and generator. They present great advantages including, low capital costs (half the price of a reciprocating engine of the same power), remote control and monitoring, low emissions and noise, no vibrations. [5]

Recent developments of micro-turbines have been focused on this technology as the prime mover for hybrid electric vehicles and as a stationary power source for the DG market. In most configurations, the turbine shaft spins up to 100,000rpm and drives a high speed generator. This high frequency output is first rectified and then converted to 50Hz. The micro-turbine systems are capable of producing 25-30% efficiency by employing a recuperator that transfers heat energy from the exhaust stream back into the incoming air stream. [36]

Due to the high turbine shaft speeds micro turbines are likely to be interfaced with power electronic inverters. Therefore if the micro-turbine would be connected to the network it could possibly stiffen up a weak distribution network by maintaining the nominal voltage where it is connected, due to the power electronic inverter. Since it has independent control of real and reactive power it can help maintain right balances of reactive power in order to increase the voltage stability of a weak network.

2.3.3 FUEL CELLS

Fuel cells are electric batteries able to convert hydrogen and oxygen into electricity, heat and water. This is unlike a storage battery that produces power from stored chemicals. There are several types of fuel cells, some of which convert natural gas and coal gas. Fuel cells have a cell that consists of an electrolyte and two electrodes. They produce power when hydrogen fuel is delivered to the negative pole (cathode) of the cell and oxygen in air is delivered to the positive pole (anode) [36]. With the aid of a catalyst, the hydrogen atom splits into a proton (H+) and an electron. The hydrogen fuel can come from a variety of sources, but the most economic is steam reforming of natural gas. The proton passes through the electrolyte to the cathode and the electrons travel in an external circuit. When the electrons flow through the external circuit connected as a load they create a DC current. The electrons combine with the hydrogen and oxygen at the cathode, producing water and heat. [19]

There are many types of fuel cells that are usually named after their electrolytes. The different types of fuel cells include, the alkaline fuel cell with an aqueous KOH electrolyte, the phosphoric acid fuel cell, the solid (polymer) proton conductor fuel cell, the molten carbonate fuel cell and the solid oxide fuel cell, whose electrolyte is a ceramic oxygen ion conductor. [34]

The individual fuel cell only outputs a voltage of 1 volt, therefore it is necessary to connect a large number of cells in series, resulting in a cell stack with the desired voltage. The stack is the major contributor to the total cost of the system. Its replacement is very costly but becomes necessary when efficiency degrades as stacks operating hours accumulate. [34]

Because fuel cells output a DC voltage, a power electronic inverter would have to interface it with the distribution network if it is to be connected with the network. The fuel cell would therefore contribute reactive power as well as active power into the network. The reactive power would again be beneficial to the voltage stability of the distribution network. One of the main disadvantages about fuel cells is its cost per kW, it is amongst the most expensive forms of generation.

2.3.4 PHOTOVOLTAICS

Photovoltaic (PV) devices convert sunlight directly to electricity. Photovoltaic systems are commonly known as solar panels. PV power systems are categorised into three application types: stand-alone, hybrid or grid connected. Stand-alone systems generally involve batteries and are used in remote locations that don't have access to the grid. An inverter is required if AC loads need to be supplied. In a hybrid system one or more auxiliary power sources such as wind or diesel generators are added to the PV system, so that loads can be supplied continuously. Grid connected PV systems is the application most relevant to this thesis, and it does not include batteries. [34]

PV solar panels are made up of discrete cells connected together in order to convert light radiation into electricity. Current units have efficiencies of 24% in the lab and 10% in actual use, below the 30% maximum theoretical efficiency that can be attained by a PV cell. [21] The power output of a PV system is directly related to the surface area of the PV cells, the efficiency of the system and the actual solar radiation, which varies hourly and daily.

PV systems produce no emissions, are reliable, and require minimal maintenance to operate. They are available for residential and commercial use, and with time manufacturers continue to reduce installed costs and increase efficiencies. However at the present moment, the major barrier to a widespread adoption of PV equipment is its high costs. PV systems are able to compete more on the basis of environmental benefits than on economics. [34]

PV systems are connected to the grid through a power electronic inverter device. The DC voltage supply is inverted to an AC voltage supply. The power electronic device controls the amount of real and reactive power introduced onto the network. It even has the ability of contributing only reactive power into the network. This would be very beneficial to a weak distribution network that requires reactive power. When a large disturbance occurs near the PV system, the power electronic device can either disconnect once it senses the disturbance or stay connected to try and strengthen the network. This however is determined by the manner in which the inverter was designed.

2.3.5 WIND TURBINES

Wind turbines convert mechanical energy into electrical energy. The usual size of individual turbines is in the range of 30kW and 1.5 MW. Wind turbines are packaged systems that include the rotor, generator, turbine blades and drive or coupling devices. The hub height reaches up to 80 metres with the rotor diameter of up to 65 metres. As the wind blows through the blades, the air exerts aerodynamic forces that cause the blades to turn the rotor. As the rotor turns its speed is manipulated to match the operating speed of the generator. [34]

The technology of wind turbines is largely determined by the concepts of the rotor and the mechanical electrical energy conversion system. The rotor is either constructed with variable blade angle (pitch regulation) or in the non-variable stall regulation. Wind turbines use induction or synchronous generators. In the conservative design an induction generator is coupled directly to the electrical network. Different types of compensation systems are used for controlling the reactive power consumption. Advanced systems use synchronous generators with pulse width modulation inverters. The generators of wind turbines experience a strong periodic torque pulsation at the frequency at which the blades pass the tower and small synchronous generators are not capable of providing adequate damping to control this torque. Small, high slip induction generators possess good damping characteristics. However as they increase in size, the transient response of induction generators to applied torque starts to resemble that of synchronous machines. [24]

Wind generators that utilise induction generators increase the probability of voltage instability on a distribution network, especially if there is a high penetration. This is because after the occurrence of a large disturbance close to the induction generator it draws large amounts of reactive power. The high demand of reactive power can lead to voltage instability or even voltage collapse if very severe. Whereas the interfaced synchronous generator poses less of a threat to the stability of a distribution network because of the intelligence of the pulse width modulation inverter. After the occurrence of a large disturbance close to the generator, the inverter has the ability of disconnecting quickly and reducing the threat of contributing to transient instability. [5]

2.3.6 HYDRO POWER PLANTS

Hydro power stations convert water pressure into mechanical shaft power, which can be used to drive an electricity generator. The vertical difference between the upper reservoir and the level of the turbine is known as the head. The water falling through this head gains kinetic energy that in turn imparts it to the turbine blades, and electricity is generated. The best turbines can have hydraulic efficiencies in the range of 80 to over 90% (higher than most other prime movers), although this will reduce with size. [38]

A hydro power plant has the ability to start up quickly and the advantage that no losses are incurred when at stand still. The installation costs of small hydro power plants ranges from $800-$2000 per kW installed. Small hydro schemes utilise both synchronous and asynchronous generators, therefore they could have two contrasting stability properties. Low head turbines tend to run more slowly and so either a gearbox or multipole generator is required. [26]

The majority of hydro generators that are connected to distribution networks are directly connected with synchronous generators. However there are a few cases of hydro generators utilising induction generators. Hydro generators have to be fitted with an additional control that is called the governor. According to Edwards et al [10], governors aid the damping of generators. The main features of a governor include [31]:

- Speed control of the hydro turbine under different conditions of start up and load fluctuations
- Fast response to load imposition and load rejection
- Shutting down inlet valve in case of over speed tripping

An additional control that is usually fitted with a hydro generator includes an Automatic voltage regulator (AVR). An AVR helps to maintain nominal voltages on the connected bus bar bus bar, as well as controlling the amount of active as well as reactive power that is injected into a network.

2.4 APPLICATIONS FOR DISTRIBUTED GENERATION

The deregulation of the electricity industry has the potential of creating an open market where applications of distributed generation could be used in managing energy costs. According to GRI [36] the applications for distributed generation include;

- Combined heat and power
- Standby power
- Peak shaving
- Grid support
- Stand-alone

The applications that are relevant in Southern Africa include standby power, peak shaving and grid support. Peak shaving and grid support is utilised by the utility to strengthen a distribution network. Standby power is mainly utilised by consumers when the power supply from the distribution network is unavailable.

2.4.1 COMBINED HEAT AND POWER

Combined heat and power (CHP), sometimes known as cogeneration, is the simultaneous production of electrical power and useful heat. Generally the electrical power is utilised inside the host premises or plant of the CHP facility, although any surplus or deficit is exchanged with the utility distribution system.[26]

Power generation technologies create a lot of heat when generating electricity. The Gas research institute (GRI) states that for the average power plant, two thirds of the energy content of the input fuel is converted into heat. [36]

2.4.2 STANDBY POWER

The electric power system in many countries including South Africa is not fully reliable. Outages do occur from time to time due to storms or accidental damage to overhead T&D systems. However some customers cannot afford to lose power, hence they require standby generators. Standby generators can also serve as a component of spinning reserve and as a method of shaving load peaks.

2.4.3 PEAK SHAVING

The cost of power varies depending on demand and the availability of generating assets. Larger customers often pay the time of use (TOU) tariff that is made of on peak and off peak rates. The on peak rate is always higher than the off peak rate. The TOU customer would therefore generate electricity during this high cost peak period, because their DG system would be cheaper to run than the peak TOU rates. [36]

2.4.4 STAND ALONE

Stand-alone distributed generators are not connected to the grid. Therefore remote areas that are not close to power grid may opt to use DG because it would be more economical for them. This is because the cost of constructing transmission lines as well a mini-substation would be high compared to purchasing a suitable DG unit. Stand alone distributed generators do not fall under the scope of this thesis due to the fact that they are not connected to the distribution network. [36]

2.4.5 NETWORK SUPPORT

Distributed generation offers grid support in different ways. These include voltage and frequency support to improve reliability, transmission capacity release and reactive power control. The use of DG can provide system benefits and reduce the need for investments in other parts of the system. Network support is essential in some electrically weak distribution networks, and it provides a cheaper alternative. [26]

2.5 IMPACT OF DISTRIBUTED GENERATION CONNECTED TO A DISTRIBUTION SYSTEM

Barker and de Mello [3] estimate that by the year 2010 distributed generation may account for up to 20% of all new generation going online. Due to the expected high increase in DG, it is important that the power system impacts are assessed accurately so that the introduction of DG units does not degrade the power quality, reliability, and control of the utility distribution system.

2.5.1 DISTRIBUTION SYSTEMS

Distribution systems can either be the radial type or the networked (ring) type. These distribution systems are generally designed to operate without generation on the distribution system or at the customer loads. The interconnection of generation on the distribution system significantly impacts the flow of power and voltage conditions at customers and utility equipment.

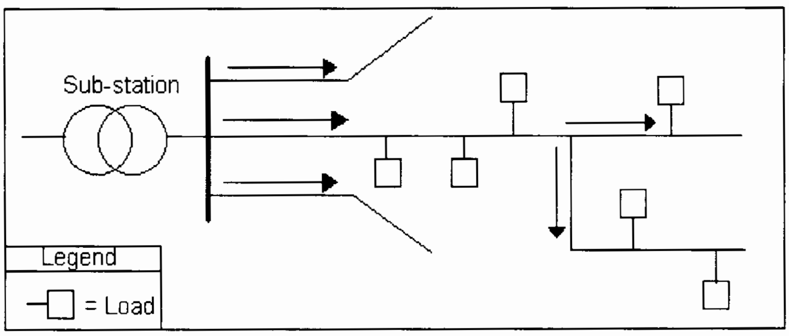


Figure 2.3: Radial distribution network [34]

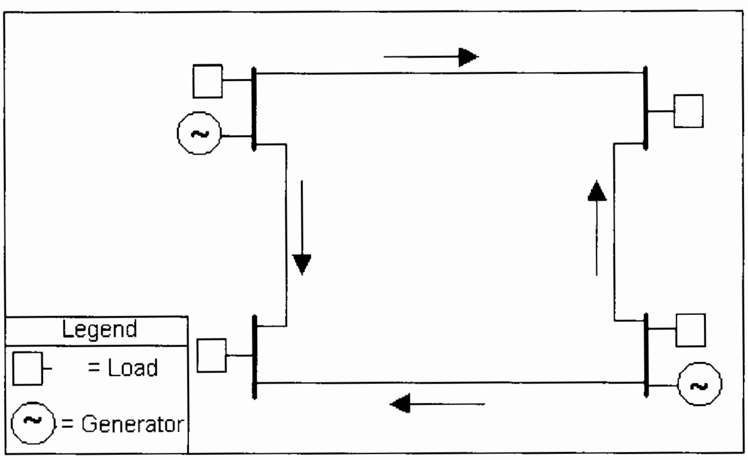


Figure 2.4: Networked (ring) distribution network [34]

The impacts can either be positive or negative. According to Barker and de Mello [3] the benefits would include:

- Voltage support and improved power quality
- Loss reduction
- Transmission and distribution capacity release
- Deferments of new or upgrade T&D infrastructure
- Improved utility system reliability

These benefits do not occur normally after the distributed generators have been interconnected. In order for distributed generation to have a positive benefit when it is interconnected with distribution systems, it must be well co-ordinated with the system operating philosophy and feeder design. This would mean paying attention to voltage regulation, voltage flicker, harmonic distortion, islanding, grounding compatibility, over current protection, capacity limits, reliability and other factors. [3]

2.5.2 VOLTAGE REGULATION AND LOSSES

Voltages on radial distribution systems are normally regulated using load-tap-changing transformers at substations, supplementary line regulators on feeders, and switched capacitors on feeders. Customer voltages have to be kept within limits specified by IEEE standard C84.1. In Southern Africa voltages on distribution networks are suppose to be kept within +/- 10% of the nominal voltage. Voltage regulation practice is based on radial power flows from the substations to the loads, and distributed generation introduces "meshed" power flows that interfere with the effectiveness of standard voltage regulation practice.

If a DG unit is applied downstream of a voltage regulator or LTC transformer that is using considerable line drop compensation, then the regulation controls will be unable to properly measure feeder demand. And according to Barker and de Mello [3] when the DG units are added, the voltage becomes lower on the feeder. The connection of DG can also result in high voltages at some customers. Persuad et al [42] also identify the same problem. This would happen if small residential DG systems share a common distribution transformer with several other residences, and this might raise the voltage on the secondary enough to cause high voltages at these customers. This can occur if the distribution transformer serving these custom ers is located at the point on the feeder where the primary voltage is near or above the ANSI upper limit. If no DG system is connected, there is a voltage drop across the distribution transformer and secondary conductors and the voltage at the customer service entrances would be less than the primary.

In order to determine if DG will cause a significant impact on the feeder voltage, the size and location of the DG, the voltage regulator settings, and impedance characteristics of the line will be considered. The impact on the feeder primary will be negligible for any individual residential scale DG unit (<10kW). However when the aggregate of many small DG units deployed reaches a critical threshold, then voltage regulation studies have to take place to ensure that voltages are kept within limits. The critical threshold at which voltage regulation studies have to commence depends on a number of factors. A reasonable rule of thumb is that if the injected current is less than 5% of the feeder loading at the interconnection point, and if all the customers had satisfactory voltage prior to the addition of the DG units, then a voltage problem on the primary is unlikely. If the injected current is much above 5% injection the potential impacts are increased. For shared secondaries with small DG units, even current injections that are less than 5% at the primary level could pose a voltage regulation risk to customers sharing the secondary. [3]

DG can also impact losses on a feeder. If the DG units are located at optimal locations they can provide the best reduction in feeder losses. Siting of DG units to minimise feeder losses is similar to siting capacitor banks for loss reduction. The only difference is that the DG units will impact both the real and reactive power flow. Large DG units have to be located after considering feeder capacity limits. The utility in charge of the network would be the one that would place the DG units in optimum positions in order to improve power quality of the network. However in a competitive electricity industry, private power producers would place their generation plants where it suits them.

2.5.3 DG CAUSING VOLTAGE FLICKER

Distributed generation can also impact the distribution system by causing voltage flicker. Voltage flicker can be a result of starting a machine (e.g. induction generator) or step changes in DG output which results in significant voltage change on the feeder. The voltage flicker results in the flickering of lighting loads, and this may be noticeable to customers. The GE flicker curve (IEEE 519-1992) can be used as a guideline in determining the severity of voltage flicker. Mitigation approaches include reduced voltage starts on induction generators as well as speed matching. Synchronous generators might require tighter synchronisation and voltage matching. Inverters would have to be controlled to limit inrush currents and changes in output levels. [3]

Wind and solar energy systems have outputs that fluctuate significantly with changes in the wind or sun intensity. These fluctuations tend to be smoother than step changes with the GE flicker curve. Therefore the GE flicker curve is a conservative curve for assessing some types of solar and wind induced voltage fluctuations. [26]

2.5.4 INTRODUCTION OF HARMONICS

Distributed generation may introduce harmonics into the network. Power electronic inverters are one of the main contributors of harmonics. The harmonics may differ in type and severity depending on the power inverter and interconnection configuration. Table 2.4 lists the harmonic current injection requirements for DGs per IEEE 519-1992. Most new inverter designs are based on IGBTs that use pulse width modulation (PWM) to generate the injected "sine" wave. These new inverters generate clean outputs that satisfy the IEEE 519-1992 requirements.

Harmonic Number	Allowed level Relative to Fundamental
<11th	4%
<11th to <17th	2%
<17th to <23rd	1.5%
<23rd to <35th	0.6%
35th or greater	0.3%
Total harmonic distortion	5%

* Only odd harmonics because even harmonics are limited to 25% of odd values

Table 2.4: Harmonic Current Injection Requirements for Distributed Generators per IEEE 519-1992 [3]

Synchronous generators are also another source of harmonics. This depends on the design of the generator windings (pitch and coils), core non-linearity's, grounding and other factors. Triple harmonics are additive in the neutral, and the third harmonic is often the most prevalent. Synchronous generators often designed with a 2/3 pitch for the windings since this produces much less third harmonic compared to the other pitches. Regrettably the 2/3 pitch machine has a lower impedance to the third harmonic and may cause more harmonic current to flow from other sources connected in parallel with it. Different arrangements can be selected to reduce third harmonic injection into the utility system. This would confine it to the DG site only. [3]

2.5.5 IMPACT ON SHORT CIRCUIT LEVELS

The fault contribution from a single small DG unit is not significant, but if many small DG units are connected to one feeder, or a few large DG units, the aggregate contribution can alter short circuit levels enough to cause fuse-breaker mis-coordination.

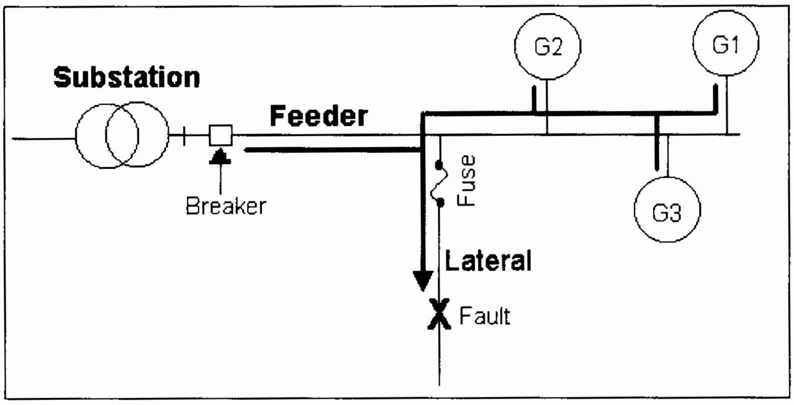


Figure 2.5: Fault contributions due to DG units 1, 2 and 3 [3]

Typical short circuit levels of DG power converters are characterised in the table below as well as reference [22]. For inverters, the fault contributions will depend on the maximum current level and duration for which the inverters manufacturer's current limiter is set to respond. Some inverters fault contribution may last for less than a cycle, in other cases it can be much longer. For synchronous generators, the current contribution depends on the pre-fault voltage, sub-transient and transient reactances of the machine, and the exciter characteristics. Induction generators also contribute to faults as long as they remain excited by any residual voltage on the feeder. For the majority of induction generators, the significant current would only last a few cycles and would be determined by dividing the pre-fault voltage by the transient reactance of the machine. The fault contribution by the DG units can assist protection equipment when detecting fault conditions, and this can be beneficial in ensuring stability. These various responses could also be used to restrict the type of DG technology that would be connected on a distribution network.

Type of Generator	Fault current into shorted bus terminals as % of rated output current
Inverter	100-400% (duration will depend on controller settings, and current may even be less than 100% for some inverters)
Separately excited synchronous generator	Starting at 500-1000% for the first few cycles and decaying to 200-400%
Induction generator or self excited synchronous generator	500-1000% for first few cycles and decaying to a negligible amount within 10 cycles

Table 2.5: Typical fault levels of Distributed generation units [3]

The above table represents the worst-case fault contributions and is only meant as an illustrative guide. For accurate analysis, the generator data should be obtained from the manufacturer. The table is also for faults at the generator terminals. These contributions will decrease as the distance from the terminals is increased.

2.5.6 IMPACT CAUSED BY ISLANDING

Islanding occurs when distributed generators continue to energise a section of the utility system that has been separated from the main utility system. The separation could be caused by the operation of an upstream breaker, fuse, or an automatic sectionalising switch. Islan ding can occur if the generator(s) can self excite and sustain the islanded section. Islanding is mostly not desired because it can lead to safety and power quality problems that will affect the utility system and loads (e.g. DG units drifting out of phase, voltage and frequency going out of limits). When the main utility supply is back, re-synchronising of the distributed generators with the utility grid has to occur.

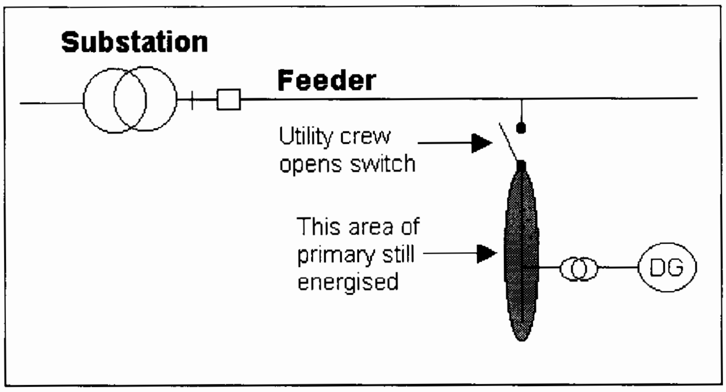


Figure 2.6: The occurrence of islanding on a distribution network [3]

Disconnecting the DG unit should a significant voltage sag or discontinuity of service on the utility side be sensed can prevent islanding. There are standards that state how long it should take the DG unit to disconnect, and these can be used as guidelines. For example, IEEE 929 recommends that small photovoltaic inverters should disconnect within 6 cycles for such events. Voltage and frequency relays can be used as anti island-protection. [22]

2.6 STABILITY OF DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

The interconnection of distributed generation with the utility distribution network offers some technical, environmental and economic benefits. However it also presents a lot of technical, regulatory, commercial and other challenges. Because distribution networks are uniquely designed and have different operating characteristics, the dynamic analysis of systems with distributed generation will also be unique. Distributed generation also includes a wide range of technologies and a variety of sizes. In order to quantify the impact of distributed generation on the different aspects of distribution network operation, a number of detailed network studies have to be carried out. One of the network studies includes stability studies on distribution networks that are connected with distributed generators. The stability studies include transient stability, voltage stability and small signal stability.

Fairey and Redfern [13] state that distributed generation instability can cause damage to the distributed generator as well as having an adverse effect on the quality of supply received by other customers connected to the distribution system, and utilities will generally require that distributed generators are designed for stable operation when operating in parallel with the distribution system. This is one of the reasons why the stability of distribution networks connected with DG needs to be clearly understood.

2.6.1 TRANSIENT STABILITY OF DISTRIBUTION NETWORKS WITH DG

The transient stability of distributed generation plays a critical role in the dynamics of distribution networks that are connected with distributed generation. According to Redfern and Checksfield [43], low inertias, high reactances, short time constants and poor inherent damping characterise distributed generators. Depending on the type of distributed generator, Redfern and Checksfield [43] state that inertia constant ranges from 0.2 to 0.3 seconds. Distributed generators are often equipped with basic automatic voltage regulators (AVRs) and are connected to distribution networks with protection operating times often in excess of the critical fault clearing time of generators. Distributed generators also have restricted reactive power output. Reactive power levels can significantly determine the voltage stability of a system, however it must be in the right quantities. The preceding factors are just some of the threats that distributed generators can pose to the stability of distribution networks.

A common indicator of transient stability of synchronous generators is their critical fault clearing time (CCT). The CCT is the maximum duration of the fault that will not lead to the loss of synchronism of one or more generators. Studies by Edwards et al [11] confirmed that the transient stability of distributed generators is generally poor. These studies also realised that if different types of distributed generators were considered, the transient stability became worse. The inertia constants of the distributed generators greatly contributed to the transient stability, the higher the inertia constant the higher the transient stability.

From the point of view of the distribution network, generator swings will result in oscillations of power and frequency, false tripping of the network protection and affect the quality of supply to the customers. From the point of view of the transmission network, the disconnection of distributed generators following instability or the operation of pole slipping protection will impact the frequency control as well as the amount of reserve required. [10]

Transient stability of distribution networks connected with distributed generation will hence be investigated further since it has been shown that distributed generators that utilise synchronous generators pose a high risk to the transient stability of distribution networks. It will be investigated further in order to understand the stability performance of distributed generators when subjected to disturbances on typically weak Southern African distribution networks.

2.6.2 VOLTAGE STABILITY ON DISTRIBUTION NETWORKS WITH DG

Jenkins and Strbac [27] state that under condition of high capacities of induction generation connected to relatively weak networks there is a possibility of voltage instability particularly if the prime mover increases above 1 pu. This is because after the occurrence of a large disturbance near an induction generator the reactive power demand from an induction generator increases. Akhmatov et al [2] compliment this statement by stating that transient short circuit faults in electrical power grids with induction generator windmills may cause voltage collapse, and wind generators are disconnected and stopped in case of such a fault in the electrical power system in order to avoid voltage collapse.

Gardiner et al [15] investigated ways of improving voltage stability on weak distribution systems. They identified that in order to improve the voltage stability the reactive power within the distribution system has to maintained and balanced. They stated that if only active power is available from a DG unit there is a high possibility of voltage instability after the occurrence of a disturbance.

With the technological advancements of power electronic inverters, power electronic inverters can be used to improve voltage stability in weak distribution networks without contributing any harmonics to the network. These semi-conductor devices have the ability of introducing only reactive power into a distribution network. This is because the inverters have the independent control of active and reactive power they supply. Voltage stability in weak distribution networks can therefore be greatly improved with the introduction of such devices. However the major drawback with this technology is the high price tag that accompanies it.

The above factors clearly portray that voltage stability is an issue when distribution networks are connected with distributed generation that utilises induction generators. Since Southern Africa has a large number of typically weak distribution networks, this problem is likely to be worse. Voltage stability will hence be investigated further by conducting voltage stability studies in further chapters.

2.6.3 SMALL SIGNAL STABILITY ON DISTRIBUTION NETWORKS WITH DG

According to Edwards et al [10], small signal stability is a function of the operating condition and structure of the power system, and of control effects. In a multi machine environment, the importance of damping of individual machines or groups of machines is related to the inertia of these machines relative to other groups. It is the damping of smaller inertia sources that determines the damping of inter-machine oscillations.

Edwards et al [10] assessed the small signal stability of distribution networks with distributed generation using eigen-analysis and individual channel analysis and design (ICAD). They used eigen-analysis since it is extensively used in power systems for assessing the damping of low frequency oscillations through modal analysis, and it can identify where controllers should be applied to alleviate dynamic concerns. ICAD was used to facilitate effective control system design and robustness assessment. The study revealed that the effect of the controllers on the inherent damping of the generator is marginal. However the turbine/governor effect was found to be greater than that of the exciter/AVR. Also poorly damped machines with low inertia had the potential of reducing the damping of inter machine oscillations of generators connected to the bulk supply system. This investigation by Edwards et al [10] reveals that even though small signal stability is an important technical issue to consider when distributed generators are connected to the distribution network, the impact of small signal stability due to this connection is not great.

Due to the findings revealed above, small signal stability will not be investigated further. This is because it has been revealed that it has a marginal effect.

2.7 VISIT TO UMIST

The objective of the visit to the University of Manchester Institute of Science and Technology (UMIST) was to investigate how stability studies could be carried out on a distribution network that is connected with distributed generation, as well as to expose the author to other distributed generation research.

According to Jenkins, one of the authors of "Embedded Generation" [26], various DG technologies have different stability properties depending on the electrical machinery they utilise. The electrical machinery includes synchronous generators, induction generators and power electronic converters / inverters. If a distributed generator utilises a synchronous generator, the stability issues that will be raised mainly revolves around transient stability because synchronous generators are likely to pole slip when they are subjected to large transient disturbances. If a distributed generator utilises an induction generator, the stability issues that will be raised mainly revolves around voltage stability because induction generators draw large amounts of reactive power when they are subjected to large disturbances. This may lead to the local network going into a state of voltage instability or even voltage collapse. If a distributed generator utilises a power electronic converter / inverter to interface itself to the distribution network, the stability issues that will be raised mainly revolves around transient stability. Small signal stability was identified by Jenkins to have a marginal impact.

2.8 DISTRIBUTED GENERATION IN SOUTHERN AFRICA

A significant number of distributed generation plants exist in Southern Africa, and due to the resources that are located in the region as well as the increased interest on DG the number of DG sites are likely to increase. Some of these plants are connected to distribution systems and are controlled by control centres of the respective countries or regions, and some are not controlled at all by control centres. However due to the fact that most of the utilities that operate in Southern Africa are monopolies, the majority of the distributed generators that exist in the region are owned and operated by the utilities. Another sector that owns a large number of distributed generators includes industry, which utilise the distributed generators for a combined heat and power application and co-generation. In this research the focus was on the Southern part of Southern Africa, which will include South Africa, Swaziland and Lesotho.

2.8.1 EMERGENCE OF DISTRIBUTED GENERATION IN SOUTHERN AFRICA

There a number of key factors that will lead or have led to the emergence of distributed generation in the Southern African region. Some of these factors are expected in the future, and did not apply in the past. These factors include [16] ;

- Technological development has increased the efficiency and reduced the cost per kW of small generating units to challenge the capital and operating efficiency of central generating stations. An increased development and lower costs are expected in the future.
- Environmental assessment of various energy sources, and concerns over the emissions they release into the atmosphere. With the introduction of the Kyoto agreement governments are expected to have increased pressure from environmental groups in the future.
- Control systems (including FACTS devices) have become more advanced and cheaper, therefore it is expected that in the future it will be easier to operate small generators in parallel with the grid.
- Proposed deregulation of the electricity industry, by relaxing central control is expected in the future.
- Political considerations led independent authorities to establish their own generating facilities in the past, connected to the South African network, but not under the control of the Eskom central system control.

HYDRO POWER PLANTS

The distributed generators that exist in the Southern African region are dominated by small hydro power plants. The hydro power plants dominate the region because Southern African is endowed with a large number of streams and rivers feeding major rivers. Storage dams that are built for mixed use (water supply, irrigation and power) are then built on the route of the major river. This form generation is acceptable to many sectors of society because of the clean power that is generated. As a result a number of hydro power stations exist in the Southern African region that can be classified as distributed generators. Table 2.6 below lists the hydro plants.

Name of Power Station	Year	Capacity MW
Umtata 1st Falls, Transkei	1979	6
Umtata 2nd Falls, Transkei	1979	11
Mbashe, Transkei	1983	42
Ncora, Transkei	1983	2
Mantsonyane, Lesotho	1989	2
Muela, Lesotho	1999	72
Ezulwini. Swaziland	1982	20
Edwaleni, Swaziland	1966	15
Mbabane, Swaziland	1953	1.5

Table 2.6: Hydro stations in Lesotho, Transkei and Swaziland [16]

These hydro power stations listed in Table 2.6 can be characterised as DG because they are connected to a voltage level of less than 132KV, and they are not centrally dispatched by the main transmission system of the region.

Since there are many hydro generators connected to the distribution networks in Southern Africa, hydro generators will be utilised as one of the DG technologies when carrying out stability studies. The hydro generators will utilise synchronous generators, just like the generators in Southern Africa.

WIND POWER PLANTS

Wind generators are non-existent in the Southern African region except for a wind farm that is to be commissioned in the Western Cape by mid 2002. This wind farm is set to be a pilot project, with the possibility of increasing the number of turbines on the wind farm. The wind farm is initially expected to have eight to ten large wind turbines and an electrical substation. The wind turbines will be horizontal axis designs. Each turbine will be connected to the on site substation by underground power cables. The turbines will be self contained and remotely monitored via telephone line. The wind farm will be connected to the nearest Eskom substation by means of a 11kV voltage overhead line. Six to ten wind turbines producing about 10MW of electricity are planned to operate by mid 2002.[20]

Due to the likely increase of the number of wind generators on the Southern African distribution network, wind generators will be utilised when carrying out stability studies in later chapters. The advantage of using wind generators is the fact that they utilise induction generators, and this offers another dimension to the stability studies that will be conducted.

PHOTOVOLTAICS

The Southern African region is also has low powered photovoltaic solar panels that exist in high numbers in rural areas. These PV panels are mainly located in areas that have not been electrified, and are used mainly to charge batteries. They are hence not connected to the network, however they have the potential to become future sources of DG if they are connected to the expanding network. Photovoltaics will hence not be part of the stability studies that are conducted in later chapters.

Photovoltaics or solar power generation is a well established technology for power supplies to sites remote from the distribution network. This form of generation can however be embedded within the distribution network and connected to the grid in order to assist with the distribution of electricity. The power ratings of these photovoltaic sites would be low, and the majority of the sites would be located on building rooftops and would be connected directly into customers' circuits.

PRIVATE INDUSTRY GENERATION

Power stations built by industrial companies (SAPPI, Sasol, sugar mills, AECI) also fall under the list of distributed generators that exist in the Southern African region. These power stations consist of steam turbines as well as diesel generators and are not permitted to export the energy from the industry to the Eskom network. Small generators that are mainly used as standby generators also fall under the distributed generator category in Southern Africa.

2.8.2 FUTURE SCOPE OF DG IN SOUTHERN AFRICA

Distributed generation has an opportunity to increase in numbers in Southern Africa due to the following driving factors; environmental legislation, research projects currently underway in the region, restructuring of the ESI in the region and network voltage support.

Many countries around the world, especially in Europe, are encouraging the installation of renewable generation technologies in preparation to meeting emissions targets as set out by the Kyoto Agreement and other local environment laws. The pressure from environmental groups in Southern Africa is relatively low compared to the pressure that is received in European countries, however world wide legislation is likely to force the countries in the region to follow suit. [5]

A number of research projects are currently underway in South Africa as well as Namibia. A possible bulk application of wind-energy generators is currently being investigated by the South African Bulk Renewable Energy Generation (SABRE-Gen) program initiated by Eskom in 1998.

This program has resulted in a wind farm in the Western Cape that will be commissioned in mid 2002. This wind farm will be a research and demonstration facility.

An additional force that is behind the emergence of DG overseas has been the worldwide trend of the Electricity Supply Industry (ESI) deregulation and unbundling. CIGRE Working Group 37.23 [5] reported that a strong increase in DG could often be seen as countries converted to unbundled utility topologies. This may be significant for DG in South Africa where the ESI is fast moving towards a de-regulated approach.

Another factor that might lead to distributed generation in the region increasing in numbers is the possible use of DG for network voltage support. If this application is feasible in a number of applications, it is likely to be a strong motivation for DG installation given the widespread need for network reinforcement in the Southern African region. An example of a project that is investigating network reinforcement by the use of DG is the Eskom Cathedral Peak diesel generator project, in Kwa-Zulu Natal.

2.9 SUMMARY

The literature survey has highlighted issues that need to be considered when distributed generation is connected to a distribution network. The literature survey revealed that there is no standard distributed generation definition at present. However a Southern African distributed generation definition has been proposed. The reason for the increased interest in distributed generation has been stimulated by technical, commercial and environmental factors. Yet, utility restructuring is essential in order to allow for the opening up of generation to allow competition.

This chapter identified wind generators and hydro generators as the types of DG technologies that will be utilized in the stability studies. The next chapter will hence focus on these types of technologies and go over their functional details.

The key issues that were raised from the literature survey when distributed generation is connected to a distribution network included;

- The Electricity demand in Southern Africa is growing at a high rate and economic methods that will cope with this demand have to be considered.
- Distributed generation technologies connect to the network by a synchronous generator, induction generator or a power electronic inverter.
- After the occurrence of nearby large disturbances synchronous generators are under the threat of transient instability, induction generations are likely to contribute to voltage

instability and power electronic inverters quickly disconnect themselves from the network depending on the manner in which they were designed.

- Distribution systems were generally designed to operate with no generation on the distribution system or at the customer loads.
- If a distributed generation unit is applied down stream of a voltage regulator or LTC transformer that is using considerable line drop compensation, then the voltage regulation controls will be unable to properly measure feeder demand.
- Distributed generation can also impact the distribution system by causing voltage flicker.
- Distributed generation may introduce harmonics into the network, and the harmonics may differ in type and severity depending on the distributed generation technology and the interconnection configuration.
- The fault contribution from several distributed generation units connected to a feeder can alter short circuit levels enough to cause fuse-breaker mis-coordination or degrade the transient stability of a network.
- Islanding operation can occur on a section of a feeder, and it can lead to safety and power quality problems that will affect the utility system and loads.
- Because distribution networks are uniquely designed and have different operating characteristics, the dynamic analysis of systems with distributed generation will also be unique.
- The transient stability of distributed generators is generally poor. Studies have realised that if different types of distributed generators were considered the transient stability becomes worse. Transient stability studies will hence be carried out in further chapters.
- Voltage stability is mainly concerned with maintaining a balance of reactive power in a system, and when there is a high penetration of DG units that utilise induction generators there is an increased possibility of voltage instability. Voltage stability studies will hence be conducted in further chapters.
- Small signal stability does not greatly impact the stability of distribution networks that are connected with distributed generation, however it must not be overlooked. Small signal stability studies will not be carried out in further chapters.
- There are a number of distributed generators that are connected to the Southern African distribution network. The number of DGs in Southern Africa is likely to increase.
- Hydro generators as well as wind generators were identified as the likely distributed generators connected to a Southern African distribution network. These two types of technologies will hence be used when carrying out stability studies in later chapters. Photovoltaics also exist in Southern Africa but they are not connected to the network because they operate in remote areas. Since photovoltaics are not connected to the distribution network they will not be part of the stability studies that will be conducted.

CHAPTER 3

FUNCTIONAL DETAILS OF DISTRIBUTED GENERATORS TO BE USED IN STABILITY STUDIES

This chapter provides the functional details and theoretical foundation on distributed generators to be used in the stability studies. The main objective of this chapter is to focus on the DG technologies that will be used in the stability simulation chapters. The DG technologies used in the simulation chapters include wind generation and hydro generation, which were identified in the previous chapter.

This chapter is divided into four sections. The first section presents the various generators that are used by distributed generators and covers their functional details. The second section presents wind power plants in preparation for the stability studies that will be conducted in later chapters. The next section presents hydro generators also in preparation for stability studies that will be conducted in later chapters. Lastly the fourth section presents the summary of the chapter.

3.1 GENERATORS USED BY DISTRIBUTED GENERATION

The distributed generators to be in the stability studies will use two forms of machinery to generate electricity into the distribution network. These forms of machinery include synchronous generators and induction generators. In this section the functional details of synchronous generators and induction generators will be presented.

3.1.1 SYNCHRONOUS GENERATORS

Synchronous generators are extensively used because they allow independent control of real and reactive power. Hydro generators in the Southern African region are commonly equipped with synchronous generators. Figure 3.1 illustrates a steady state synchronous generator with a constant terminal voltage. Small generators that are connected to a utility distribution system have little control of its terminal voltage and none over the system frequency.

POWER GENERATED BY SYNCHRONOUS GENERATORS

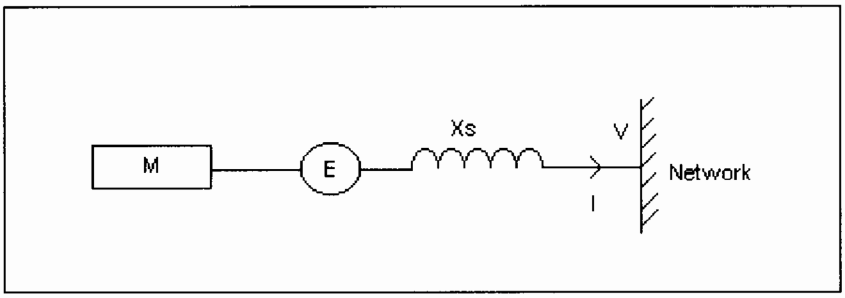


Figure 3.1: Small synchronous generator connected to a network [24]

M = mechanical prime mover
E = excitation voltage
X_s = synchronous reactance
V = voltage of network
I = current

The phasor diagram of the above diagram would therefore be represented as follows:

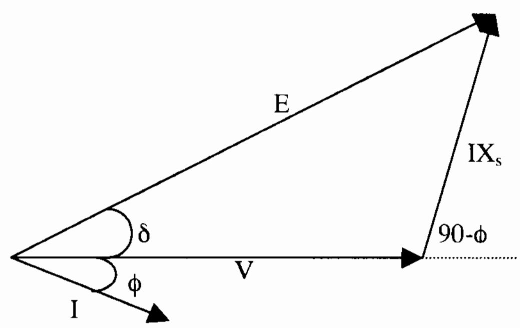


Figure 3.2: Phasor diagram of synchronous generator [24]

cosϕ = power factor
δ =power angle
IX_s at 90° to I

The real power (P) and the reactive power (Q) per phase for this circuit is given by :

$$P = \frac{EV}{X_s}\sin\delta \qquad 3.1-1$$

$$Q = \frac{EV}{X_s}\cos\delta - \frac{V^2}{X_s} \qquad 3.1-2$$

Due to the fact that under normal operation the rotor angle δ is usually less than 30°, the cosine term of equation 3.1-2 remains fairly constant. Equations 3.1-1 and 3.1-2 demonstrate how;

- The real power output (P) is controlled by the governor of the mechanical prime mover which determines the applied torque and hence the power angle (δ).
- The reactive power (Q) is controlled by the excitation system which varies the magnitude of the excitation voltage (E)

The operating chart of a synchronous generator is formed directly from the phasor diagram of Figure 3.2. The phasor diagram is simply scaled by multiplying by V/X_s, which is a constant. The locus of the new phasor VI then describes the operation of the generator.

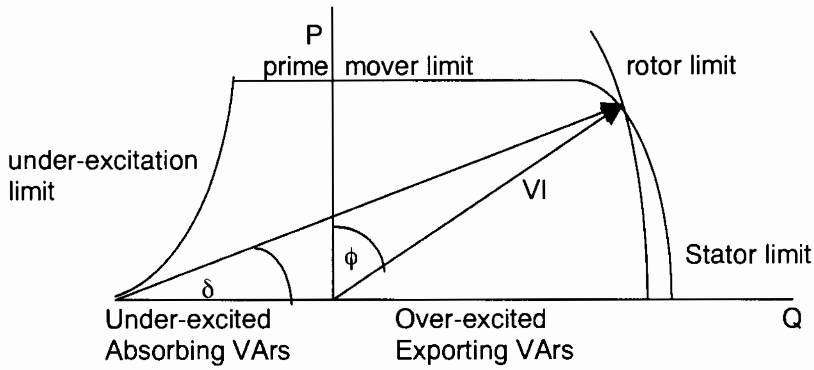


Figure 3.3: Operating chart of a synchronous generator [26]

The chart exemplifies that a synchronous generator may operate over a wide range of real and reactive powers and that the reactive power can be controlled independently of real power. Various limits are applied to account for: (i) the maximum power available from the prime mover (ii) the maximum current rating of the stator (iii) the maximum excit ation and (iv) the minimum excitation for stability and/or stator end winding heating.[24]

CONTROL OF SYNCHRONOUS GENERATORS

The excitation system of a synchronous generator consists of an exciter and a controller. The controller is also referred to as an AVR (automatic voltage regulator), and it regulates the voltage of the generator.

The excitation and governor systems of a generator can significantly impact its performance during network disturbances. However if equation 3.1-1 is re-written for transient conditions, it can illustrate the potential benefit of fast acting excitation systems.

$$P = \frac{E_f' V}{X'} \sin \delta \qquad 3.1-3$$

Where $E_f'$is the transient internal voltage of the generator and X' is the transient reactance.

The transient reactance is determined by the generator design but the transient internal voltage (E_f') can be increased by a fast acting excitation system. Thus by using a high response excitation system, the power transfer capability of the generator can be maintained, even if the network voltage (V) is depressed by a fault. Hence the generator can remain stable for longer clearing times, or at higher loading conditions than would be possible with a slower AVR/exciter.

The provision of tight, fast-response control over the generator terminal voltage unfortunately has the effect of reducing generator damping, and can in some circumstances lead to oscillatory instability. The contribution of a round rotor synchronous generator to a three phase fault is usually described by an expression of the form [26];

$$I = E_f\left[\frac{1}{X_d}+\left(\frac{1}{X_d'}-\frac{1}{X_d}\right)e^{-\frac{t}{T_d'}}+\left(\frac{1}{X_d''}-\frac{1}{X_d'}\right)e^{-\frac{t}{T_d''}}\right]\cos(\omega t+\lambda)+E_f\left(\frac{1}{X_d''}\right)e^{-\frac{t}{T_a}}\cos\lambda \qquad 3.1-4$$

Where,

X_d = direct axis synchronous reactance
X'_d = direct axis transient reactance
X''_d = direct axis sub-transient reactance
E_f = prefault internal voltage
T'_d = direct axis transient short circuit time constant
T''_d = direct axis sub-transient short circuit time constant
T_a = armature (DC) time constant
λ = angle of the phase at time zero
ω = system angular velocity

The sub-transient, transient and synchronous reactances are used to represent the performance of the machine at different times after the fault defined by the corresponding time constants. The armature (DC) time constant is used to describe the decay of the DC offset of the fault current. [24]

The X/R ratios of synchronous machines are much larger than those of distribution circuits. Therefore if a fault occurs close to a synchronous machine, it will have an armature time constant and hence a DC component which is much longer than for a remote fault.

3.1.2 INDUCTION GENERATORS

Induction generators referred to as asynchronous generators are widely used by distributed generation technologies. Wind generators are commonly equipped with induction generators with squirrel cage rotors. Wound rotor induction generators are used in some specialised distributed generating units, but these are not common. The reason for the use of a squirrel cage rotor is the simplicity of their construction, the lack of requirement for synchronising and the damping they introduce into the drive train of the generating set. The difference in speed between the rotor and the stator mmf (slip speed) provides the damping of an induction generator. However as the size of induction generators increases the natural slip decreases therefore the transient response starts resembling that of a synchronous generator. [24]

POWER GENERATED BY INDUCTION GENERATOR

An induction generator is, in principle, an induction motor with torque applied to the shaft. However there may be some modifications made to the machine design to optimise its performance as a generator. The operation of an induction generator can be understood using the familiar induction motor equivalent circuit. [26]

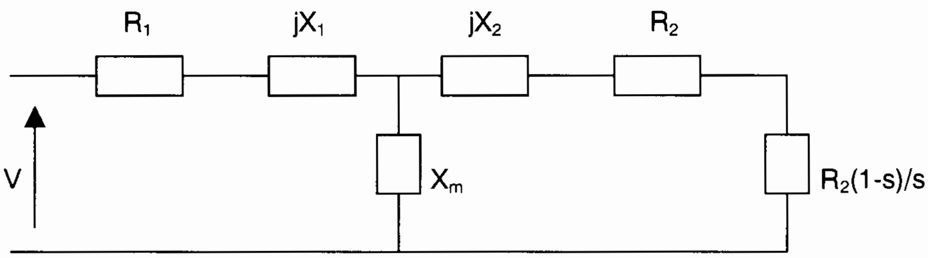


Figure 3.4: Steady state equivalent circuit of induction machine. Positive phase sequence for balanced operation [46]

The slip speed (s) is given by,

$$s = (\omega_s - \omega_r)\omega_s \qquad 3.1-5$$

Where ω_s is the angular velocity of the rotor, which is negative for generator operation.

The mechanical power of the rotor is given by,

$$P_{mech} = I_2^2 R_2 (1-s)/s \qquad 3.1-6$$

And the rotor copper losses are equivalent to,

$$P_{losses} = I_2^2 R_2 \qquad 3.1-7$$

A simple analysis of the circuit relies either on moving the magnetising branch to the supply terminals or by using a Thevenin transform to eliminate the shunt branch. When considering the approximate equivalent circuit, then the current flowing in the rotor circuit is given simply by,

$$I_2 = \frac{V}{(R_1 + R_2/s + j(X_1 + X_2))} \qquad 3.1-8$$

And the total power supplied to the rotor is the sum of the copper losses and the developed mechanical power,

$$P_{rotor} = I_2^2 R_2 / s = \left[\frac{V}{(R_1 + R_2 / s + j(X_1 + X_2))} \right]^2 R_2 / s \qquad 3.1-9$$

The equivalent circuit may also be used to derive the circle diagram of an induction machine, illustrated in Figure 3.5. The circle diagram describes the normal operating locus of an induction machine in terms of real and reactive power. This is similar to the synchronous machine operating chart. A key difference between the synchronous machine and the induction machine is the induction generator can only operate on the circular locus and there is always a defined relationship between real and reactive power. The control of the power factor of an induction generator is therefore impossible. The circle diagram illustrates that an induction generator only draws reactive power and can not supply reactive power. This property of the induction generator has the potential of creating voltage stability problems on distribution networks if high capacity induction generators are connected to weak distribution networks.[26]

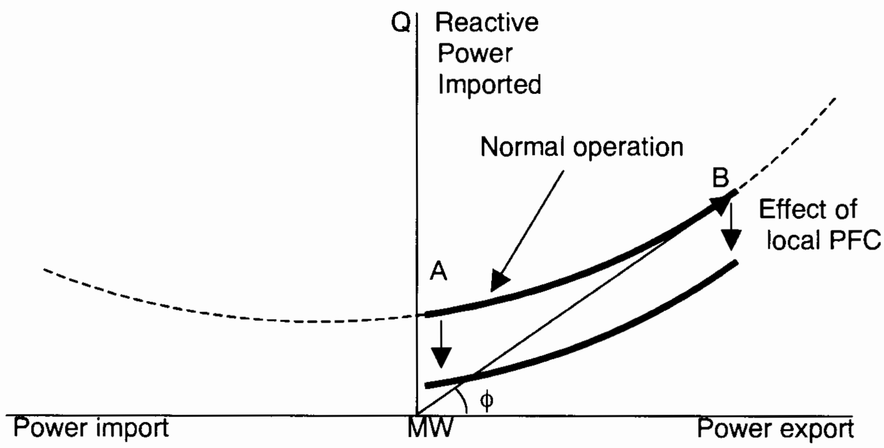


Figure 3.5: Induction generator circle diagram [26]

At point A the induction generator is at synchronous speed, drawing reactive power from the network to magnetise its core, and with its internal power losses supplied by a small applied shaft torque. No real power is exported to the network. When more torque is then applied to the shaft, real power is exported however additional reactive power is imported, as seen at B. Unlike the synchronous machine the reactive power requirement of an induction generator is directly linked to the real power output and the power factor varies from zero at A to 0.9 at B.

One of the ways used to improve the power factor of the induction generator is to fit local power factor correction (PFC) capacitors at the terminals of the generator. The power factor correction equipment has the effect of shifting the circle diagram, as seen by the network, downwards along the Y-axis. [26]

CONNECTING INDUCTION GENERATORS TO A DISTRIBUTION NETWORK

If a large induction generator, or a number of small induction generators, is connected to a network with a low short circuit level, then the network source impedance, including the effect of any generator transformers, can become significant. The equivalent circuit is then extended, as shown below, to include the source impedance (network) in the stator circuit.

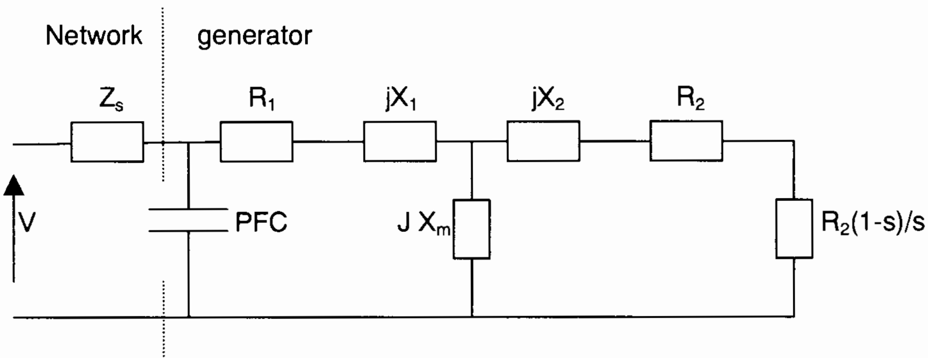


Figure 3.6: Steady state equivalent circuit of the induction machine connected through a source impedance [26]

The power factor correction equipment has the potential of creating a resonant circuit between the capacitance and the inductive reactance of the induction generator. This can lead to self-excitation, then the reactive power requirement of the generator can be supplied locally and, if the induction generator is disconnected from the network, then the generator will continue to develop a voltage. As the speed and hence the frequency of the 'islanded' generator increases, potentially hazardous over voltages may be created and can cause damage to load equipment connected to the isolated part of the network fed from induction generators with power factor correction.

During network disturbances the induction generator has low impedance to unbalanced voltages. It therefore draws large currents when the phase voltages of the distribution system are not balanced. The following negative phase sequence equivalent circuit of an induction machine confirms this analogy.

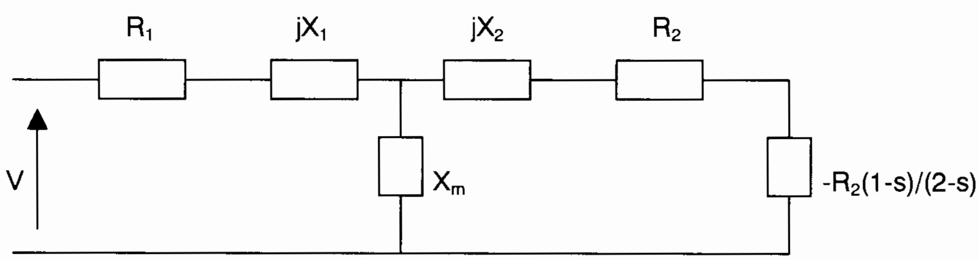


Figure 3.7: Negative phase sequence equivalent circuit of an induction machine (unbalanced operation) [26]

In normal operation the slip tends to zero and so the rotor effective resistance is reduced to $R_2/2$. The effect of the unbalanced current is to increase heating in the generator and to impose a torque ripple on the drive train. Unbalanced voltage conditions often occur on rural distribution networks due to the connection of single-phase loads. Induction generators that are connected on weak rural networks therefore experience difficulty due to excessive unbalanced currents.

The behaviour of an induction generator under fault conditions is different to that of a synchronous generator. A three-phase fault on a distribution network interrupts the supply of reactive power needed to maintain the excitation of the induction generator and there is therefore no sustained contribution to a symmetrical fault.

An induction generator on its own cannot produce a terminal voltage. It requires a source of reactive power to develop a magnetic field. The reactive power source can be obtained from a distribution network. Therefore when an induction generator is connected to a network there is an initial magnetising inrush transient, followed by a transfer of real and reactive power to bring the induction generator to its operating speed. The magnetising inrush transient and the transfer of real and reactive power to accelerate and decelerate the generator is controlled using anti-parallel thyristor soft-start units as shown below.

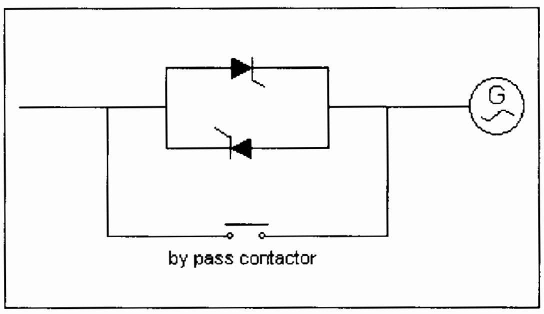


Figure 3.8: Soft-start unit for an induction generator (only one phase shown) [24]

The soft-start units are placed in each phase of the generator connection. They are operated by controlling the firing angle of the thyristors so building up the flux in the generator slowly and then also limiting the current which is required to accelerate the drive train. When the full voltage has been applied, often after a couple of seconds, the by pass contactor is closed to eliminate any losses in the thyristors.

3.2 WIND POWER PLANTS

Mankind has used wind energy for centuries for milling, pumping and a lot of other applications. However, it is only in the latter half of this century that humans have started to explore the use of wind energy to generate electricity. Wind farms have now been established in many countries around the world including Holland, Denmark, United Kingdom, New Zealand and the United States. Projects in developing countries such as Namibia, Morocco and South Africa are underway. By the end of 2002, South Africa will have its first wind farm in the Western Cape. The wind farm will be connected to the Eskom distribution network at a voltage level of 11kV. [18]

3.2.1 POWER GENERATED BY WIND TURBINES

Wind turbines convert mechanical energy into electrical energy. This is caused by the movement of air that propels the blades. The blades then turn along with it the axle that is attached to the blades. The axle carries over the energy to a gearbox and finally to the generator where the electricity is generated. The total mechanical power available from the wind at a wind speed, v, on the swept area of a rotating turbine, A, is given in accordance with; [26]

$$P_{wind} = \frac{1}{2} C_p \rho_{air} A v^3 \qquad 3.2-1$$

Where,

C_p = power coefficient
P_{wind} = Power (W)
v = wind velocity (m/s)
$A = \pi R^2$ = swept area of rotor disc (m^2)
ρ_{air} = density of air (1.225 kg/m^3)

Because the total power available from the wind is proportional to the cube of the wind speed, it is therefore important to locate wind turbines in areas of high mean annual wind speed. It is often likely that the area with high mean annual wind speed have relatively weak electrical distribution networks, because they are located in rural/remote places. The integration of the wind turbines to weak electrical distribution networks therefore raises stability concerns. The low density of air explains why wind turbine rotors of a given rating are much larger than that of a hydro turbine. This is because the density of water is much larger than the density of air. The force exerted on the rotor is proportional to the square of the wind speed, therefore the wind turbine must be designed to withstand large forces during storms. Most modern designs use a three-bladed horizontal axis rotor as this gives a good value of peak C_p together with an aesthetically pleasing design. The power coefficient C_p is a measure of how much of the energy in the wind is extracted by the turbine rotor. It varies with rotor design and the relative speed of the rotor and wind to give a maximum practical value of approximately 0.4. [26]

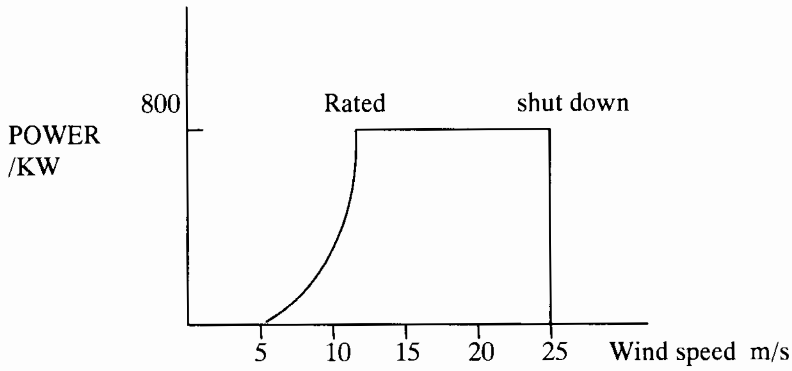


Figure 3.9: Wind turbine power curve [26]

The above wind power curves indicate the output of the wind turbine at different wind speeds. Power is only generated at speeds higher than the cut-in speed of 5 m/s. The output power then increases rapidly with wind speed until it reaches its rated value and is then limited by some control action of the turbine. At a wind speed of 25 m/s , shut-down speed, the rotor is parked for safety.

3.2.2 TORQUE VARIATIONS

The torque from a horizontal axis wind turbine rotor contains a periodic component at the frequency at which the blades pass the tower. The cyclic torque is caused by the variation in wind speed seen by the blade as it rotates. The variation in wind speed is due to a combination of the following; tower shadow, wind shear and turbulence. A fixed wind turbine translates this rotor torque variation into a change in output power and hence a voltage variation on the network. The voltage variation is referred to as voltage 'flicker' because of the effect it has on incandescent lights. In general the torque fluctuations of individual wind turbines in a wind farm are not synchronised and so the effect of large wind farms is reduced as the variations average out. [26]

3.2.3 FIXED SPEED WIND TURBINES

Fixed speed wind turbines that use induction generators are simpler and more robust. Network connected fixed speed wind turbines that utilise a synchronous generator are not common, because it is not practicable to include adequate damping in a synchronous generator to control the periodic torque fluctuations of the aerodynamic rotor. The following diagram shows a schematic diagram of a fixed-speed wind turbine.

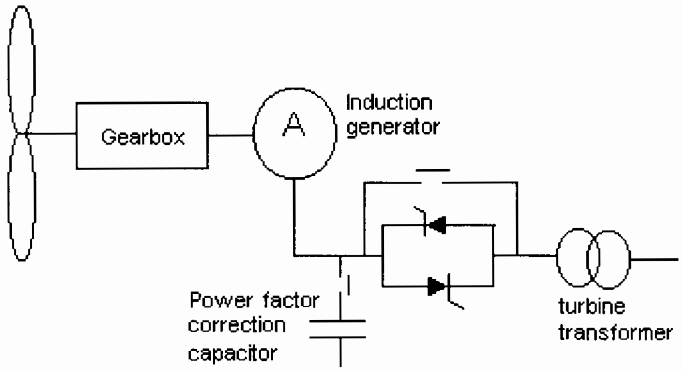


Figure 3.10: Schematic diagram of a fixed speed wind turbine [26]

3.2.4 VARIABLE SPEED WIND TURBINES

Variable speed operation can increase the energy captured by the aerodynamic rotor by maintaining the optimum power coefficient over a wide range of wind speeds. However, in order for this to be done the speed of the rotor has to be decoupled from the frequency of the network through some form of power electronic converter. Two voltage source voltage converter bridges are used to interface the wind turbine drive train to the network. The generator converter is used to maintain the voltage of the DC link, while the network converter is used to control the output power and hence the torque on the rotor. The generator may be either synchronous or induction, and pulse width modulated (PWM) switching pattern is used on the converter bridges. Significant electrical losses occur as the power is transferred through the variable-speed equipment. Nevertheless, the advantages that are offered by the variable speed operation include; [26]

- A reduction in mechanical loads which allows lighter mechanical design
- Smoother output power

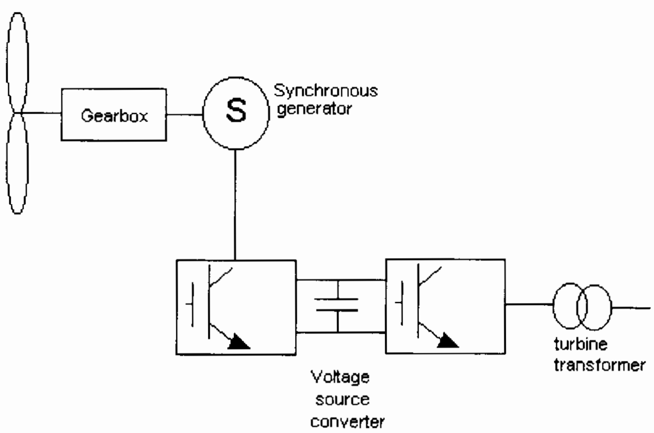


Figure 3.11: Variable speed wind turbine [26]

3.3 HYDRO POWER PLANTS

A hydro power plant consists of turbines connected to electric generators and the structures necessary to channel and regulate the flow of water to the turbines. Hydro power stations convert the energy of flowing water into electricity. There are a number of hydro power stations in Southern Africa that can be classified as distributed generators. The power rating of these power stations ranges up to 72MW. These power stations are listed in Table 2.6 in chapter 2.

3.3.1 POWER GENERATED BY HYDRO POWER PLANTS

Hydro generators convert water pressure into mechanical shaft power, which can be used to drive an electricity generator. The power output of a hydro system is given by the expression; [48]

$$P = QH\eta\rho g \qquad 3.3-1$$

Where,

P = output power (W)
Q = flow rate (m^3/s)
H = effective head (m)
η = overall efficiency
ρ = density of water ($1000kg/m^3$)
g = acceleration due to gravity (m/s^2)

Equation 3.3-1 shows that the power generated is proportional to the flow rate and the effective head. However a high effective head is more desirable to increase power output because it reduces the required flow rate and hence the cross sectional area of the penstock (the pressurised pipe bringing water to the turbine).

3.3.2 MAIN COMPONENTS OF A HYDRO POWER PLANT

The main components of a hydro power plant can be separated into three units. The units include; (i) the main inlet valve (MIV) and turbine, (ii) the generator (iii) the electrical control equipment and unit auxiliaries.

MAIN INLET VALVE AND TURBINE

Water from the dam is conveyed to the turbine casing through a pipeline known as the penstock pipe. The main inlet valve (MIV) is used to isolate or stop water supply to the turbine when the generator is shutdown. The MIV is electrically operated. When a power failure occurs while the machine is running with the MIV open, the MIV is manually closed by hand. Under running conditions the MIV is opened and the water passes through a series of adjustable guide vanes inside the turbine casing which control the flow of water into the turbine runner which in turn controls the power generated by the generator. The runner is connected to the generator rotor shaft and the flywheel and the force of the force of the water acting against the blades of the runner cause the runner to turn, driving the generator. The water is finally discharged into the tailrace through the discharge pipe.

The governor controls the guide vane opening and closing. When the guide vanes are fully open, maximum power flows through the turbine and hence maximum power is generated. When the guide vanes are nearly closed a small quantity of water flows through the turbine hence only a small amount of power is generated.

GENERATOR

All the hydro generators that exist in Southern Africa are synchronous generators. The generator consists of the stator core and windings (stationary part), the rotor shaft and flywheel (moving part), bearings and bedplate (moving part) and the cooler.

The bedplate supports the stator and the bearings. The bearings support the rotor shaft that turns inside the stator. The rotor shaft is bolted together with the flywheel. The runner is bolted onto the rotor shaft inside the turbine. A fan is mounted on the flywheel which circulates the air inside the generator. Cool air is drawn from the cooler and is circulated through the windings. The stator winding has temperature detectors located at different positions around the windings. These detectors are used to protect the windings from high temperature conditions.

ELECTRICAL CONTROL EQUIPMENT AND UNIT AUXILIARIES

The generator exciters form part of the generator control equipment. Exciters control the generating voltage as well as the amount of reactive power that is generated by the generator. Hydro generators utilise brush-less exciters or brush exciters. Brush-less exciters are the more recent technology and are preferred to the brush exciters because they require less maintenance and are more efficient.

The lubrication system forms part of the unit auxiliaries and its main function is to supply oil to the bearings. It is essential that the oil is pumped to the bearings while the rotor shaft is turning. The bearings have temperature sensing devices for protection against over temperature. The hydro generator also has a governor oil pumping set with an air receiver that supplies oil to the governor, which in turn operates the guide vane servomotor that opens and closes the guide vanes. The governor is used to control the rotor speed at any load.

3.4 SUMMARY

Functional details of distributed generators that will be used in the stability studies were presented. The chapter started by introducing the electrical machinery that is used by the distributed generators, which included synchronous generators and induction generators. The two DG technologies that are likely to be found in Southern Africa and will be used in the stability studies were then presented.

Synchronous generators were found to allow independent control of real and reactive power. By controlling the excitation of the synchronous generator one can control the amount of reactive power imported or injected contributed by a synchronous generator. Induction generators on the other hand require reactive power in order to operate and do not allow independent control of active and reactive power. The control of an induction generator power factor was found to be impossible.

The power generated by wind power plants was found to be mainly influenced by the wind velocity, because total power available from wind is proportional to the cube of the wind velocity. Wind generators were found to cause voltage flicker on a distribution network that is undesirable to customers connected. From the two types of wind turbines that were presented fixed wind turbines that use induction generators were established to be simpler and more robust compared to variable speed wind turbines, which cost more. The power generated by hydro generators was found to be proportional to the flow rate and the effective head. When covering the main components of a hydro generator the, turbine, generator and excitation system are the most important.

CHAPTER 4

THEORETICAL STABILITY ASPECTS OF DISTRIBUTED GENERATION

This chapter covers relevant theoretical aspects of stability that will be useful when conducting stability studies in the stability simulation chapters. The previous chapter presented hydro generators and wind generators since they will be used in the stability simulation chapters. This chapter creates the theoretical stability foundation for carrying out the stability studies with hydro generators and wind generators connected to the distribution network. Some of the concepts that are focused on were identified in the literature survey as well as the chapter on the functional details of distributed generation.

This chapter is divided into nine sections. The first section covers the stability concepts and definitions that differentiate the different types of stability. The second section describes two classical stability analysis methods that are indirectly utilised in the stability simulation chapters. The third section presents models of network components and generator components that will be used in the stability studies. The fourth section outlines the different types of faults and sources of short circuit currents that regularly occur on a distribution network. The fifth section presents the various stability issues that are raised by connecting distributed generators to distribution networks, in preparation for the stability studies. The sixth and seventh section covers the stability properties of induction generators as well as synchronous generators respectively. The eighth section describes the power system tool that is used to carry out the stability studies. Finally, a summary of the key findings of the chapter is presented.

4.1 STABILITY CONCEPTS AND DEFINITIONS

Power system stability is that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [7]. In order for a power system to be stable it has to satisfy angle stability, frequency stability, and voltage stability.

A power system is at equilibrium when the voltage magnitude and angle at each bus are such that power flows from buses where there is an excess of generation over demand to buses where demand exceeds supply. At each bus, there is thus a balance between the power generated, the power consumed and the power transmitted to and from other buses. [26]

Figure 4.1 below classifies the different components that make up power system stability, and separates them into different categories. These different categories however fall under power system stability. This research considered the different stability aspects when investigating the stability of distribution networks that are connected with distributed generation. A lot of attention will however be focussed on transient stability as well as voltage stability, because these are the forms of stability were identified by the literature survey to be the main forms of stability that need to be investigated.

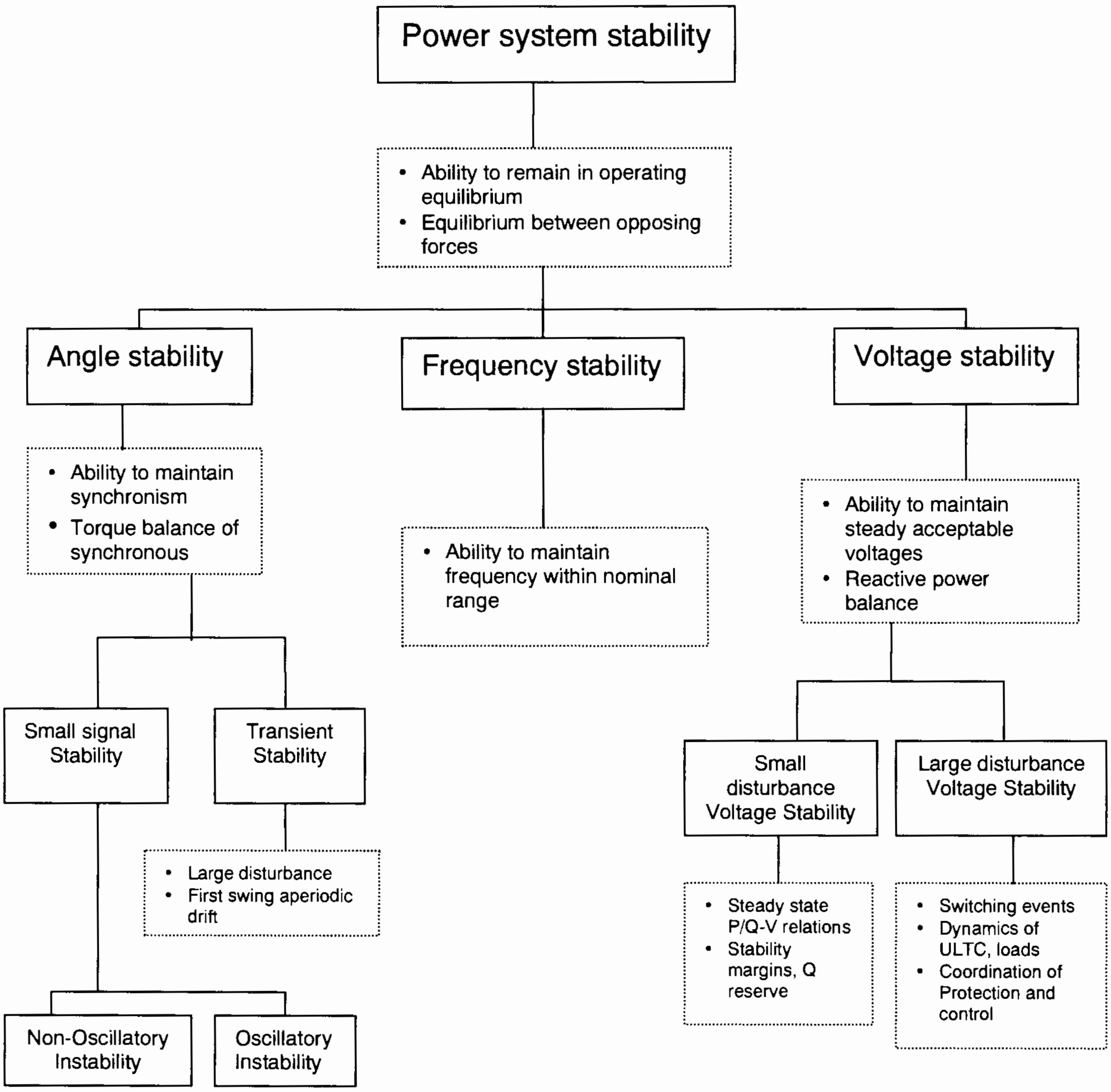


Figure 4.1: Classification of power system stability [7]

4.1.1 ANGLE STABILITY

Angle stability is related with the ability of interconnected synchronous machines of a power system to remain in synchronism under normal operating conditions and after being subjected to a disturbance. In distributed generation the synchronous generators could include hydro generators, reciprocating engines, some wind turbines and gas turbines. The angle stability problem involves the study of the electromechanical oscillations in power systems. Angle stability depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. When a synchronous generator loses synchronism with the rest of the system, its rotor tends to speed up or slow down relative to the speed required to generate voltages at system frequency. This slip results in large fluctuations in the machine power output, current and voltage. The large fluctuations in machine power output, current and voltage could probably degrade the quality of supply on the local distribution network. This would be the case if the generator protection or the distribution network protection has not been triggered. [7]

After the occurrence of a disturbance, the change in electrical torque of a synchronous machine can be separated into two components:

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega \qquad 4.1-1$$

Where;

$T_S \Delta\delta$ is the component of torque change in phase with the rotor angle disturbance $\Delta\delta$ and is referred to as the synchronising torque component; T_S is the synchronising torque coefficient. $T_D \Delta\omega$ is the component of torque in phase with the speed deviation $\Delta\omega$ is referred to as the damping torque component; T_D is the damping torque coefficient.

In order for system stability to be satisfied, both components of torque for each of the synchronous machines have to exist. Not enough synchronising torque leads to instability through an aperiodic drift in rotor angle. On the other hand, insufficient damping torque results in oscillatory instability.[31]

Rotor angle stability is characterised into small signal stability and transient stability.

4.1.1.1 Small signal stability

Small signal stability is also referred to as small disturbance stability. It is concerned with the ability of the power system to maintain synchronism under small disturbances. The small disturbances would include small changes in load conditions and generation conditions. The disturbances are considered to be sufficiently small that linearisation of system equations is permissible for purposes of analysis. When small signal stability is lost it can be of two forms;

(i) steady increase in rotor angle due to lack of sufficient synchronising torque, or (ii) rotor oscillations of increasing amplitude due to lack of sufficient damping torque. A system response to small disturbances depends on a number of factors including initial operating conditions, strength of network and type of generator excitation control used. [7], [31]

Small signal stability is not expected to be a significant problem when distributed generation is connected to a distribution network, as pointed out in the literature review. The reason why it is not a problem is because the effect of the controllers on the inherent damping of the generator is marginal, as found by Edwards et al [10].

4.1.1.2 Transient stability

Transient stability is concerned with the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. Stability depends on both the initial operating state of the system and the severity of the disturbance. The major disturbances may include loss of generation, line switching operations, faults and sudden load changes. These disturbances can occur on distribution networks as well transmission networks.

Following a disturbance, synchronous machine frequencies undergo transient deviations from synchronous frequencies, and machine angles change. The objective of transient stability study is to determine whether or not the machines will return to synchronous frequencies with new steady-state power angles. Changes in power flows and bus voltages are also of concern. [31]

Two factors that indicate the relative stability of a generating unit include the angular swing of the machine during and following fault conditions, and the critical fault clearing time (CCT). The inertia constant, H, and the transient reactance, X'_d, of the generating unit have a direct effect on both of these factors. The following equations show that the smaller the H constant, the larger the angular swing during any time interval. [31]

$$\Delta\delta = \delta_{n-1} + kP_{a,n-1} \qquad 4.1-2$$

$$k = \frac{180f}{H}(\Delta t)^2 \qquad 4.1-3$$

Factors that affect transient stability

There are numerous factors that affect the transient stability of a power system. These include: [4]

- The strength of the network

- The characteristics of the generating units, including the inertia of the rotating parts and such electrical properties as transient reactance and magnetic saturation characteristics of the iron in the stator and rotor
- The speed at which the faulted lines or equipment can be disconnected from the system and how rapidly the lines can be restored to service by automatic reclosing of the network line
- The speed at which generator excitation systems respond, since disturbances are usually accompanied by rapid reductions in system voltage and rapid restoration of the system voltage to normal is important in maintaining stability

Distribution networks that are found in Southern Africa are dominated by electrically weak networks. They are generally weak because the impedance between the generators is high relative to that of developed countries. The long radial distribution networks that dominate the Southern African region result in high impedances. Since one of the factors that affect the transient stability of a power system is the strength of a network, the weak networks are prone to transient instability when connected with distributed generators and subjected to transient disturbances.

The literature review chapter revealed that the general characteristics of distributed generators cause the transient stability of distributed generators to be generally poor. Case study 2 in chapter 5 investigates the effect of the different electrical parameters on the transient stability of the distributed generator in order to realise the impact of the characteristics of the generating units.

The speed at which faulted lines or equipment can be disconnected, is another factor that affects transient stability. This is because if the fault is cleared quickly the connected distributed generator can possibly recover and go back to a stable operating point. If the fault clearing time exceeds the critical fault clearing time (CCT) of the distributed generator, the generator goes into an unstable operating point, which can have undesirable effects on the distribution network to which it is connected.

The speed at which generator excitation systems respond also impacts the stability of distribution networks connected with distributed generation. As mentioned in chapter 3, high response excitation systems maintain the power transfer capability of the generator even if the network voltage is depressed by a fault, hence the generator can remain stable for longer clearing times.

4.1.2 FREQUENCY STABILITY

Frequency stability is the ability of a power system to maintain the frequency within a nominal range, following a severe system upset that may or may not result in the system being divided into sub-systems. [7]

Frequency stability depends on the ability to restore balance between system generation and load with minimum loss of load. A system operating at constant frequency must be in a state of power balance. Thus the total system-generated real power must equal the system real power loads, losses, and tie flows out of the system. When this balance is upset, the system frequency will begin to change. Too much generation will result to the frequency increasing, and too little generation will result to the frequency dropping.

This type of stability problem is almost irrelevant for distributed generators that are connected to larger grids. This is because even if a distributed generator connected to a distribution network over generates or loses stability, the distribution network frequency (system frequency) cannot be affected due to the large grid to which it is connected. Since the majority of the distributed generators that are likely to be connected to the distribution network are likely to be rated at less than 50MW, generation of this magnitude is unlikely to alter the frequency of a large grid. Due to the above reasons frequency stability is not investigated further.

4.1.3 VOLTAGE STABILITY

Voltage stability is concerned with the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance.[31]

Voltage instability may occur in the form of a progressive fall or rise of voltage of some busses. The main factor causing voltage instability is the inability of the power system to maintain a proper balance of reactive power throughout the system. The heart of the problem is usually the voltage drop that occurs when active power and reactive power flow through inductive reactances associated with the distribution network. The concept of voltage stability is related to transient stability of a power system. The analysis of voltage stability usually requires simulation of the system modelled by non-linear differential-algebraic equations. [7]

Voltage stability is a local phenomenon, however it can lead to a wide spread impact. Voltage collapse is more complex than voltage stability and is usually a result of a sequence of events accompanying voltage instability leading to a low voltage profile in significant part of the power system. Distributed generators that are likely to cause voltage instability on a distribution network include DG plants that utilise induction generators, as revealed in the chapter 3. This is because after the occurrence of large disturbances induction generators are likely to draw large amounts of reactive power that can result in voltage instability.

Voltage stability is characterised into the following two categories:

4.1.3.1 Large disturbance voltage stability

Large disturbance voltage stability is concerned with a system's ability to maintain steady voltages following large disturbances. Major contributors of large disturbance voltage instability include asynchronous machines. For severe voltage dips, the reactive power demand of asynchronous machines increases, contributing to voltage collapse. This would be after the occurrence of a large disturbance. [49]

Asynchronous motors supplying loads with constant torques draw constant power independent of applied voltage. However, during faults or periods of low voltage, they decelerate as the electrical torque is not adequate to meet the required mechanical torque. Following the clearing of the fault, the motor may not regain the original speed and continues to decelerate leading to stalling of motors that in turn aggravates the low voltage problem. [39]

Since Southern Africa is dominated with electrically weak distribution networks, after the occurrence of a large disturbance on these types of networks severe voltage dips occur which result in high reactive power demands from induction generators and some dynamic loads. Large disturbance voltage stability is hence investigated further in Chapter 6 on electrically weak distribution networks..

4.1.3.2 Small disturbance voltage stability

A power system at a given operating state is small-disturbance voltage stable if, following any small disturbance, voltages near loads are identical or close to the pre-disturbance values. The small disturbance could be incremental changes in system load. This form of stability is determined by the characteristics of load, continuous controls, and discrete controls at a given instant of time. The concept of small-disturbance voltage stability is related to steady state stability and can be analysed using a small signal model of the system. [31]

Small signal stability is not investigated further because it is determined by the characteristics of load, continuous controls, and discrete controls at a given instant of time. Since small disturbance voltage stability is determined by continuous and discrete controls, generation that is connected to the distribution network would indirectly affect this type of stability, hence this type of study is beyond the scope of this thesis.

4.1.3.3 Voltage collapse

Following voltage instability, a power system undergoes voltage collapse if the post-disturbance equilibrium voltages near loads are below acceptable limits. Voltage collapse may be total (blackout) or partial. [23]

Voltage collapse is a possibility on electrically weak networks. Case study 4 in Chapter 6 investigates voltage collapse on electrically weak networks further. Protection coordination is an important factor that can determine whether a local distribution network undergoes voltage collapse or not. Again, the high reactive power demands of induction generators are one of the main contributing factors that determine voltage collapse.

4.2 CLASSICAL STABILITY ANALYSIS

Traditionally, a complete power system has previously been simplified and reduced to either a one machine to infinite bus or two-machine system in order to simplify and perform stability analysis. One of the methods used to determine stability is the equal area criterion. This method is limited to one machine and infinite bus, or to two machines. Swing curves are used to assess the stability of multi-machine systems, and it is a method that solves swing equations. It involves solving large high order differential equations and algebraic equations and is therefore time consuming and necessitates the use of high-speed digital computers. These classical stability analysis methods can be useful when carrying out stability studies of distribution networks connected with distributed generation. Some of the concepts from these methods were used to explain behaviour of distributed generators after being subjected to disturbances in section 4.7.

4.2.1 EQUAL AREA CRITERION

The equal area criterion is a method that can be used for a quick prediction of stability. The equal area criterion is a simple graphical method for determining whether a one-machine infinite bus system will remain stable. It provides a useful representation of the factors that affect stability. In practical systems, it may be used to obtain a first approximation of the stability limit. [17]

There are some basic assumptions that are made when using this method. They include; constant input power, no damping and constant field flux linkage or constant voltage behind transient reactance. The input power is assumed to constant because the action of the prime mover and the governor are so slow that, for the first swing, their effects can be neglected. [30]

The equal area criterion is based on the application of the power transfer curves. Before the fault the generator operates along the power transfer curve defined by the generator internal emf E, the infinite bus voltage V and the equivalent reactance X_o given by the equation below. The generator angle and the electrical power input are related by equation 4.2-1, which is similar to equation 3.1-1;

$$P_e = \frac{EV}{X}\sin\delta \qquad 4.2-1$$

Where,

P_e = Electrical power

δ = Steady state angle

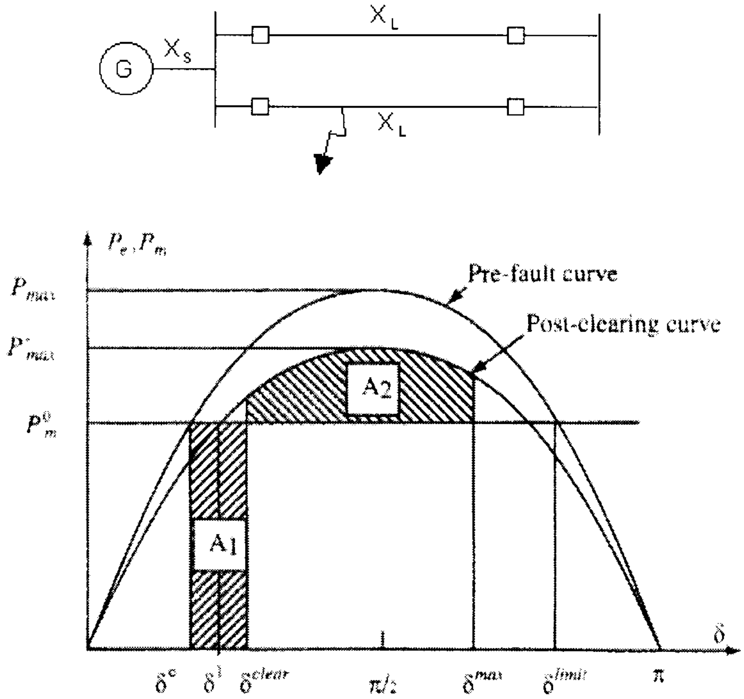


Figure 4.2: Power angle relationship after the occurrence of a disturbance [26]

When a fault occurs there is no decelerating electrical torque and the rotor accelerates, increasing the angle δ. By the time the fault has cleared at t^{clear}, this angle has reached the value δ^{clear}. The kinetic energy stored by the rotor is proportional to the area labelled A_1 in Figure 4.2. After the fault clears, the voltage at bus A is restored, and the power can again be transmitted between the generator and the infinite bus. However, this transmission takes place on a newer power transfer curve because the equivalent impedance between the internal emf and the infinite bus is now

$$X_1 = X_s + X_l \qquad 4.2-2$$

Where,

X_1 = Total reactance with one line disconnected

X_s = Source reactance

X_l = Line reactance

Because one of the transmission lines has been taken out of service, as shown in the network in Figure 4.2. Since $X_1 > X_0$, this post-clearing fault is below the pre-fault curve. For $\delta = \delta^{clear}$, the electrical power transferred on this new curve is larger than the mechanical power applied by the prime mover. The decelerating torque is thus larger than the accelerating torque and the rotor starts to slow down. However, the rotor angle δ will increase to a value δ^{max} such that the area $A_1$is equal to the area A_2. If δ reaches δ^{limit} before the equal area criterion is satisfied, the electrical power absorbed by the network becomes smaller than the mechanical power provided by the prime mover. This will lead to the rate of increase of δ to be positive and stability will be irretrievably lost. On the other hand, if δ^{max} is less than δ^{limit}, δ starts decreasing and stability is maintained. [26]

δ^{limit} is referred to as the critical stability limit. It is a crucial point that determines whether a synchronous generator will be able to maintain synchronism or pole slip after being subjected to a disturbance.

One important drawback to the equal area approach is that even if the critical-clearing angle may be calculated, the critical-clearing time may not. However if the swing equation is solved for δ as a function of time, the critical clearing time can be calculated.

4.2.2 SWING EQUATION

The swing equation describes the motion of the machine rotor. It gives the relationship between the inertia torque and the resultant of the mechanical and electrical torques. In its simplest form, the swing equation is given by [35];

$$J\theta_m = T_a \qquad 4.2-3$$

Where J is the moment of inertia of the machine, and T_a is the acceleration torque. However the motion of a generator rotor is described by the following second order equation,

$$J\frac{d^2\theta_m}{dt^2} = T_m - T_e \qquad 4.2-4$$

Where

θ_m is the angular position of the rotor with respect to a stationary axis,

T_m is the net mechanical input torque and

T_e is the electromagnetic torque

If both sides of the equation are multiplied by the nominal (rated) rotor speed, ω_m, we get

$$M\frac{d^2\theta_m}{dt^2} = P_m - P_e \qquad 4.2-5$$

Where

$M = J\omega_m$ is the angular momentum

P_m = mechanical power

P_e = electrical power

It is also convenient to express θ_m as

$$\theta_m = \omega_m t + \delta_m \qquad 4.2-6$$

δ_m is the rotor angle with respect to a synchronously rotating reference frame with velocity ω_m. Therefore this leads to the swing equation,

$$M\frac{d^2\delta_m}{dt^2} = P_m - P_e \qquad 4.2-7$$

The most common representation of the swing equation is in terms of the inertia constant H, the acceleration power P_a and the angular position δ with respect to the rotating reference. This representation is shown below;

$$\frac{2H}{\omega_m}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \qquad 4.2-8$$

where

$$H = \frac{J\omega_m}{MVA} \qquad 4.2-9$$

The solution of the swing equation gives δ as a function of time. A graph of the solution is known as the swing curve. Thus, if a power system contains n number of synchronous machines, n swing equations must be solved simultaneously. The direct closed form solution is not applicable, considering that differential equations are involved. A recursive approach is used to solve this equation. Once the solution is obtained, the swing curves indicate whether the system is stable or unstable.

The point-by-point method uses iterative techniques to solve the swing equations. Some variables are assumed constant during a time step and others are calculated. At the end of the time step, new values for the variables that are previously assumed constant are recalculated and the process repeated.

When solving the swing equation, the accelerating power is assumed constant during the time step. The final values of ω and δ are calculated from the initial values. Once these values are obtained a new value of the accelerating power is calculated. Since the mechanical power is constant during the first swing, the problem is reduced to calculating the electrical power. This is obtained by solving the power flow equations of the network. [35]

4.3 MODELS TO BE USED IN STABILITY STUDIES

In traditional power system stability theory, the problem of stability was originally associated with synchronous generators connected to the transmission system (voltage levels above 132kV). With the increased interest and introduction of dispersed generators to the distribution system (voltage levels below and including 132kV), distribution analysts for the first time have to consider issues of stability. In preparation for stability studies that will be carried out in later chapters the models of the generators, networks and loads will be covered in this section.

4.3.1 DISTRIBUTION NETWORK MODEL

The distribution system is that part which connects the bulk power source/s and the consumer service switches. Distributed generation in Southern Africa is likely to be found on two different types of distribution networks. These networks include;

- Radial distribution networks
- Networked (ring) distribution networks

Stability studies will be carried out these two types of network structures. In Southern Africa the dominant type of distribution network is the radial distribution network, therefore more studies will be done on it. Distribution networks are defined to operate at a voltage level of less than or equal to 132kV. Networks that operate at voltage levels above 132kV are defined to be transmission networks. This definition does not apply in some Southern African countries, for example Swaziland. Swaziland considers its 400kV, 132kV and 66kV networks transmission networks, and voltage networks that operate below 66kV are defined as distribution networks. This is because Swaziland is a small country and it only recently constructed a 400kV transmission line that runs across the country. However for the purposes of this thesis, distribution network will be defined to operate at voltages below and including 132kV. This means all the networks that will be studied will be less than or equal to 132kV.

4.3.1.1 Radial distribution networks

The radial distribution network is the dominant type of distribution network in Southern Africa and it is typically found in the non-urban areas. Radial distribution networks are the simplest and cheapest form of supplying power to consumers. They are specifically designed to deliver electrical energy from substation transformers to end-use customers. Radial systems are designed with a substation transformer at the centre and the distribution lines radiating out towards the loads. While there can be many radial distribution lines emanating from a substation each load is typically served by only one line. The system is designed so that power always flows in one direction. A radial system offers a less reliable power source than a networked system because it lacks redundancy. However, the radial system and its protection equipment are less complex and less expensive than the networked system. [34]

A radial network with parallel circuits is another type of network that can possibly be found in Southern Africa. This type of network would have characteristics of both the radial as well as the ring type of distribution network. The radial network with parallel circuits offers some redundancy therefore offers a more reliable power supply.

Figure 4.3 shows a typical topology of the radial distribution network that will be used in the investigation. It has 3 voltage levels 132kV, 33kV and 11kV. The distributed generators are connected to the 11kV bus bar. In Southern Africa a high number of radial distribution networks are electrically weak relative to radial networks in developed countries. Electrically weak radial distribution networks in Southern Africa have high impedance between generators due to the extremely long distribution and transmission lines as well as the infrequent interconnection of the network. The distribution networks in developed countries have a high interconnection level between the distribution networks, which results in a relatively lower impedance between the generators.

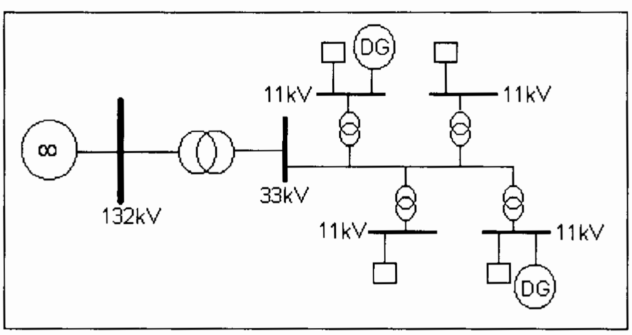


Figure 4.3: Radial distribution network with distributed generators connected

4.3.1.2 Networked (ring) distribution networks

The ring distribution network is typically found in urban areas. It is designed to provide highly reliable service to the end-use customer. The networked system offers reliability advantages over the radial system because it provides multiple power sources for loads [31]. Figure 4.4 shows a typical topology of the ring distribution network that will be utilised in the investigation. This network only has two voltage levels, 132kV and 22KV. The distributed generators are connected to the 22kV bus bar. The voltages of the distribution networks would range up to a maximum of 132KV.

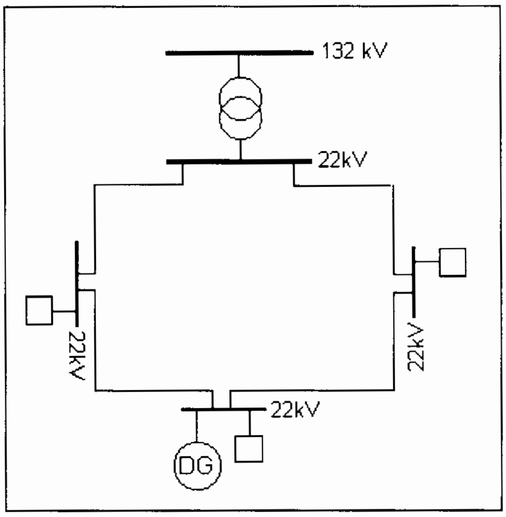


Figure 4.4: Networked distribution network with a distributed generator connected

4.3.2 DISTRIBUTED GENERATOR MODEL

The performance of generating units plays an important role in determining the stability of a power system. Generator models are developed depending on the generator type and the type of controllers it will utilise. Modern stability simulating software packages encompass generator models that have been developed for stability studies. The selection of a generator model in stability studies is however influenced by factors such as the study being undertaken, the range of operating conditions to be considered, electrical proximity of other generators of similar size, type of disturbance being considered and the availability of data. [32]

DG technologies can either be made of synchronous machines and asynchronous machines. However some technologies utilise power electronic converters, or a combination of machines and converters. Hydro generators and wind turbines were selected as the types of DG to be used in the stability studies. Distributed generator models for these technologies will hence be required to model distributed generators in the stability studies. Hydro generators utilise synchronous generators and wind turbines utilise asynchronous machines.

4.3.2.1 Synchronous generator model

The synchronous machine model that is utilised in the stability studies is from Digsilent Power factory simulation software, and is shown in Figure 4.5. Digsilent is the simulating software that will be used in the stability studies and it is presented in section 4.8. The model shown in Figure 4.5 is used to represent the synchronous generator as an element with no control units added to it. However it may be added with additional models such as exciters, prime mover, and stabilisers.

In Figure 4.5 below,

Ug	=	machine terminal voltage (model input)
Ig	=	machine stator current (model output)
Ue	=	excitation voltage
Pt, Mt	=	mechanical turbine power
Rhou,g	=	generator load angle

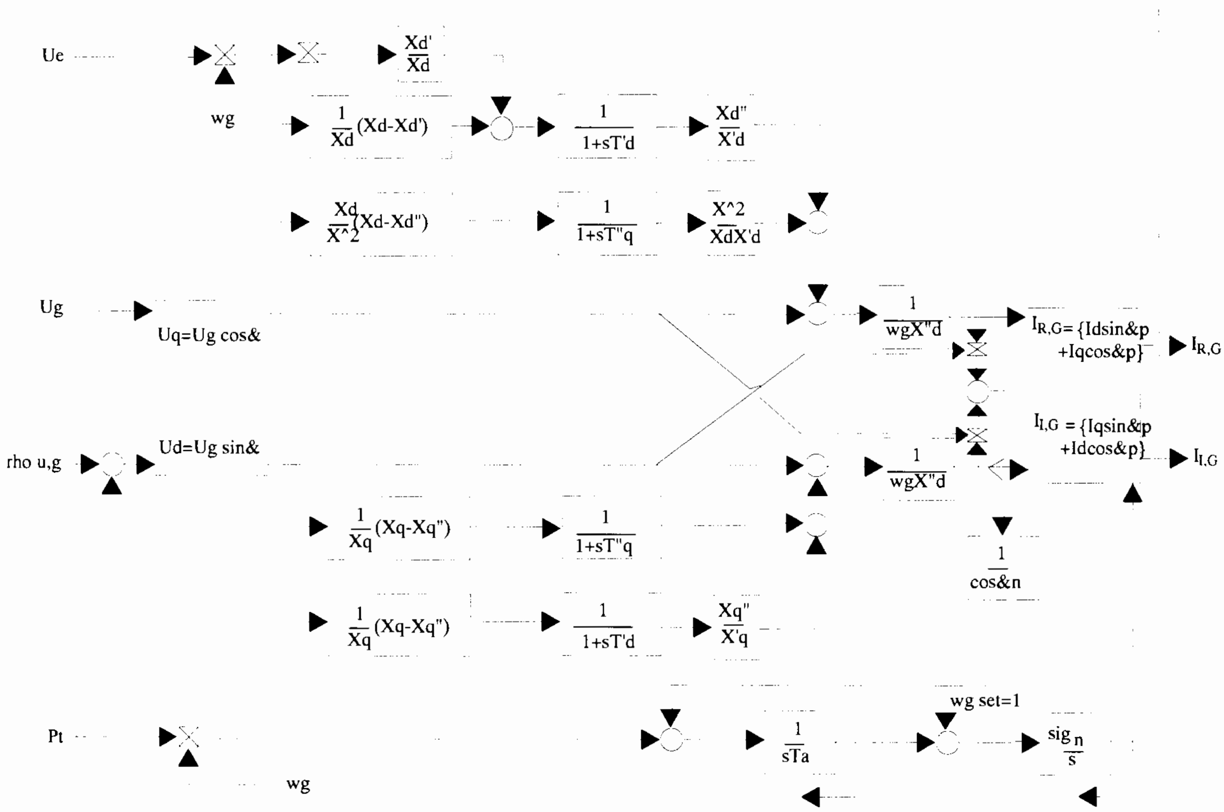


Figure 4.5: Synchronous generator model [9]

4.3.2.2 Induction generator model

The induction generator model that is used in the stability studies is from Digsilent Power factory simulation software, and is shown in Figure 4.6. This model is used to represent the induction generator as an element with no control units added to it.

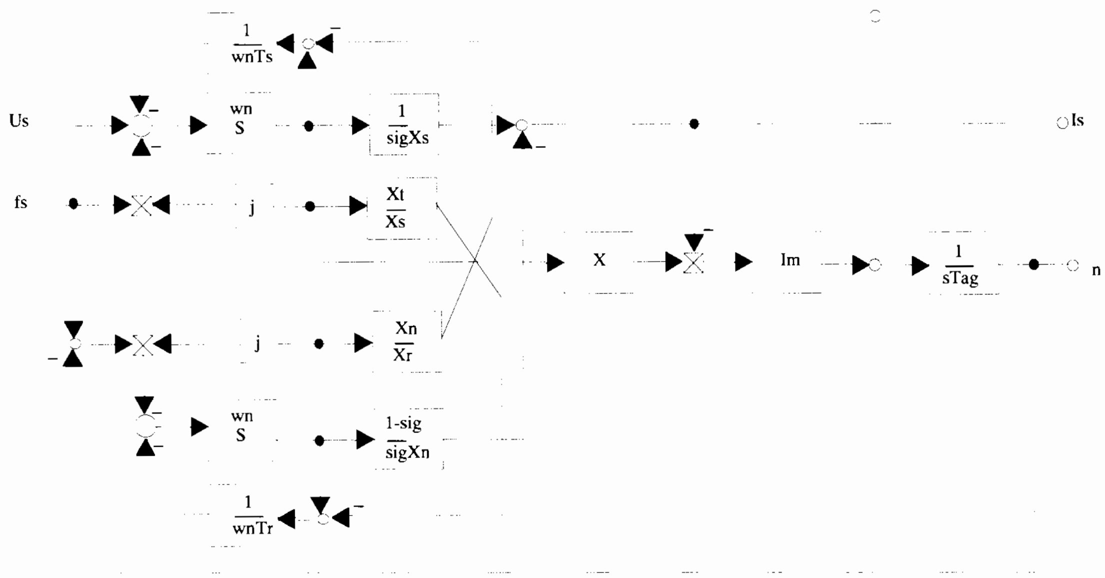


Figure 4.6: Induction generator model [9]

4.3.3 LOAD MODEL

The stable operation of a power system depends on the ability of generating plants to always match the electrical load on the system. Load characteristics therefore have an important influence on system stability.

A load model is a mathematical representation of the relationship between a bus voltage (magnitude and frequency) and the power (active and reactive) or the current flowing into the bus-load [23]. Load models are required to represent customer loads. Load modelling is complex due to its dynamic property. Load characteristics significantly affect the dynamic behaviour of power systems. The load composition changes with the time of the day, the consumer's life style, the weather, the state of the economy and other factors. It would therefore be difficult to develop an accurate load model because of the unpredictable nature of loads. However, approximate load models are utilised to estimate customer loads. Since approximate load models are introduced to estimate customer loads some error in the results is introduced. The error can be reduced by carrying out a study that will come up with exact load models of the loads investigated.

The type of load class that needs to be represented in this research includes residential, commercial and industrial loads. A mixture of static and dynamic loads represents these loads. A load model that mixes static loads as well as dynamic loads was used to approximately represent the required network loads.

4.3.3.1 Static loads

Static loads are passive or non-rotating loads. Polynomials or some algebraic functions like exponentials represent them. Static loads are voltage dependent, frequency dependent or both. The frequency component contributes to the system damping. The instantaneous operating frequency and terminal voltage determine the active and reactive power components of the load. It is very difficult to determine the frequency dependency of the load because load frequency tests are rarely performed. [30]

4.3.3.2 Dynamic loads

Dynamic loads vary considerably and rapidly to changes in voltage and frequency. A large part of dynamic loads for which detailed studies have been performed is induction motors. This is the case since most of the loads in an industrial power system are induction motors. [30]

4.3.3.3 Polynomial load model

A polynomial load model is a static load model that represents the power relationship to the voltage magnitude as a polynomial equation, usually in the following form:

$$P = P_o\left[a_1\left(\frac{v}{v_o}\right)^2 + a_2\left(\frac{v}{v_o}\right) + a_3\right] \qquad 4.3-1$$

$$Q = Q_o\left[a_4\left(\frac{v}{v_o}\right)^2 + a_5\left(\frac{v}{v_o}\right) + a_6\right] \qquad 4.3-2$$

The parameters of this model are the coefficients (a_1 to a_6) and the power factor of the load. The model consists of the sum of constant impedance, constant current and constant power terms. If this, or other, models are used for representing a specific load device, and P_o and Q_o should be the power consumed at rated voltage. However, when using these models for representing a bus load, V_o, P_o and Q_o are normally taken as the values at the initial system operating condition for the study. [23]

4.3.3.4 Load model used in stability studies

The load model that is used in the stability studies is from Digsilent Power factory simulation software. The load model has neither been specified as a synchronous or asynchronous machine nor as a shunt but as a general active or reactive load. The load model is a combination of a dynamic load, static load and a "special" load that is defined by a user-defined graph. The proportional mix of dynamic, static and special behaviour is chosen by setting percentages for the different types of loads. In the different case studies different proportional mixes of dynamic and static power are chosen depending on the load being modelled, each case study explains the rationale behind the selected proportion. Figure 4.7 illustrates the load model used.

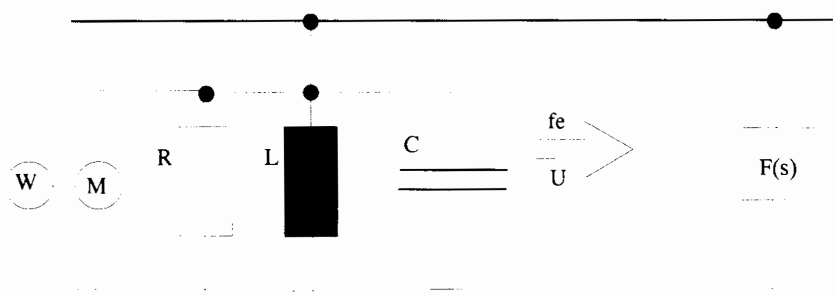


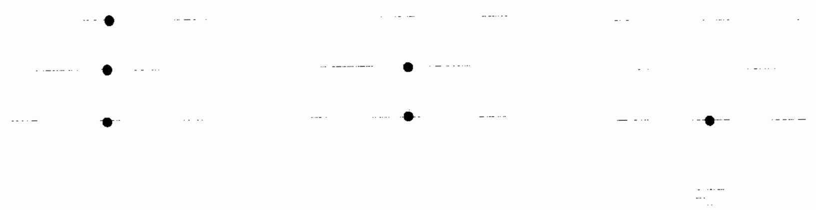
Figure 4.7:Digsilent load model [9]

4.4 DISTURBANCES

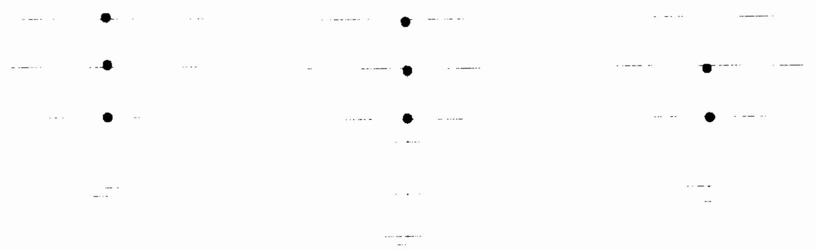
Typical disturbances that occur on distribution networks include faults, operational switching, abrupt changes in load flow and the effects of systematic voltage controllers. The most common disturbances are faults. The type of disturbance that will be introduced in the stability simulations is the three-phase fault. This type of disturbance was selected because it often results in the highest fault current, therefore the highest disturbance. This section outlines different types of faults and sources of short circuit currents that regularly occur in power systems.

4.4.1 TYPES OF FAULTS

The types of faults that occur in power systems include overload, over voltage and short circuit faults. In a three-phase system, the type of faults that occur in practice are illustrated in Figure 4.8 below, and the most common of these faults is the short circuit of a single phase to ground.



(a) Three phase fault | (b) Phase-phase fault | (c) Single-phase to ground fault



(d) Three-phase to ground fault | (d) Three phase to ground fault (grounded with arcing resistor) | (e) Two-phase to ground fault

Figure 4.8: Different types of faults on three phase systems [49]

The earth faults that may flow on a particular power system depend mainly on the earthing system used. They can also be influenced by the soil resistivity of the place where the fault occurs.

4.4.2 SOURCES OF SHORT CIRCUIT CURRENTS

The magnitude of short circuit currents depends on different sources that generate them. The magnitude is also dependent on the reactance of the source as well as the system reactance up to the fault location. Sources of short circuit currents include [33];

- Electric utility systems
- Generators
- Synchronous motors

4.5 STABILITY ISSUES RAISED BY DISTRIBUTED GENERATORS

The connection of distributed generators onto distribution networks raises stability concerns. The stability concerns are however influenced by the mode of operation, type, size and characteristics of the distributed generators; layout and characteristics of the distribution network; type and size of the loads; network control devices; and the extent of penetration of the network by other distributed generators. In this section stability issues that are raised by the connection of distributed generation are discussed.

4.5.1 CHARACTERISTICS OF DISTRIBUTED GENERATORS

Distributed generators are generally characterised by low inertias, high per unit reactances, short transient time constants and poor inherent damping. These characteristics together with long fault clearance times associated with the types of protection used on distribution networks all contribute to the increased probability of instability. [43]

The higher the generator inertia constant H, the more stable the generator will be. This is because the generator will swing less following a disturbance. However the inertia constant is proportional to cost. Therefore the higher the inertia constant the more expensive the generator will be. The inertia constant is calculated using the equation 4.5-1 and this calculation is independent of the network,

$$H = \frac{1}{2}\frac{J\omega_m^2}{S_B} = \frac{kinetic \cdot energy \cdot stored \cdot in \cdot megajoules}{Rating \cdot in \cdot MVA} \qquad 4.5-1$$

Transient time constants of a generator determine the critical fault clearing time (CCT) of generators. The critical fault clearing time is the maximum duration of the fault that will not lead to the loss of synchronism of one or more generators, it is dependent on the network.

High per unit reactances result in short critical fault clearing times, therefore the distributed generators easily get into a state of instability. However low per unit reactances result in longer critical fault clearing times, therefore a longer duration fault will result in the generator losing stability. The relationship between critical fault clearing time and per unit reactances is investigated in Chapter 5.

4.5.2 DISTRIBUTION NETWORK DESIGNS

Distribution networks were designed to receive bulk power from the transmission network and to distribute the power to customers. The real and reactive power would therefore flow from higher to lower voltages. However, with significant penetration of distributed generation the power flows may become reversed and the distribution network is no longer a circuit supplying loads but a system with power flows and voltages determined by the generation as well as the loads. [25]

The layout and characteristics of the distribution network can influence the stability of the distribution network. For example, there would be a stability difference between a long radial distribution network and a highly interconnected ring distribution network because the radial distribution network has an electrically weak network, due to the branch impedances. Where as the ring distribution network has a relatively lower impedance because it has interconnections.

4.5.3 DISTURBANCES OCCURRING ON THE NETWORK AND AFFECTING STABILITY OF DG

Distribution networks are prone to a large number of transient disturbances. These disturbances include faults, changes in load condition and abrupt changes in load flow. Step changes in electrical parameters such as terminal voltage (due to faults) and total reactance (changes in connected impedance) occur very quickly, resulting in significant and severe changes in electromechanical transient torques, large rotor oscillations and the chance of losing stability.

Transient instability of a distributed generator results in loss of synchronism between the generator and the supply to which it is connected. This causes the distributed generator to pole slip with respect to the utility network's grid supply. The pole slipping initiates dramatic fluctuations in the currents both absorbed and provided by the distributed generator. [43]

One of the most severe disturbances that can occur on a network is a three-phase fault. If this type of fault occurs near the terminals of the distributed generator, transient instability of the distributed generator could occur. The clearing of this type of fault would be governed by the response of inverse definite time delay over current relaying, IDMT. This type of protection can be of the order of half a second, and considering the fact that the critical clearance time for a typical distributed generator is of the order of 300 milliseconds, transient instability can be expected following such a fault. [43]

The type of disturbance that will be used in the stability studies is a three-phase fault. This type of disturbance is the most severe disturbance that would threaten the stability of the distributed generators, hence it would be the most suitable type of disturbance to investigate the stability of distribution networks connected with DG.

4.5.4 CONNECTION OF DISTRIBUTED GENERATION ON A WEAK DISTRIBUTION NETWORK

One of the properties of a weak distribution network is it has a very low X/R ratio, which results from the relatively high impedance of the distribution lines. Therefore changes in both active and reactive power flows have significant effects on the steady state voltage changes. A weak distribution network suffers voltage fluctuations when load current flowing through the resistive and reactive impedances of the line varies, especially after a disturbance on the network. After the occurrence of a disturbance equation 3.1-1 is not valid. The fluctuations are generally worse towards the end of the line and are accentuated if the load is concentrated near the end of the system. Active power flow is a significant cause of voltage drop on distribution networks with low X/R ratios, DGs could provide an improvement in the voltage stability of that network because it is be able to inject reactive power onto the network. [15]

The steady-state stability limit of induction generators can also limit their application on very weak distribution networks because a very high source impedance, or low network short-circuit level, can reduce their peak torque to such an extent that they cannot operate at the rated output. [7]

4.5.5 REACTIVE POWER CONTRIBUTION BY DISTRIBUTED GENERATORS

Some distributed generators can control the amount of reactive power they output. Distributed generation technologies that utilise synchronous machines can control the amount of reactive power they output. DG technologies that utilise asynchronous machines instead draw reactive power from the network they are connected to. During large disturbances induction machines draw large quantities of reactive power, and depending on the strength of the network this can lead to voltage instability.

4.6 STABILITY PROPERTIES OF INDUCTION GENERATORS

In order to analyse the stability of distributed generators that utilise induction generators, it is useful to go over the stability properties of induction generators. This section covers stability considerations, generator over speeding, stability limits and dynamic stability improvements of induction generators.

4.6.1 STABILITY CONSIDERATIONS

The static stability limit of induction generators can be explained using their Torque Vs Speed characteristic. In order to explain the stability consideration of induction generators, the Torque Vs Speed characteristic of an induction generator of a standard wind turbine is again used.

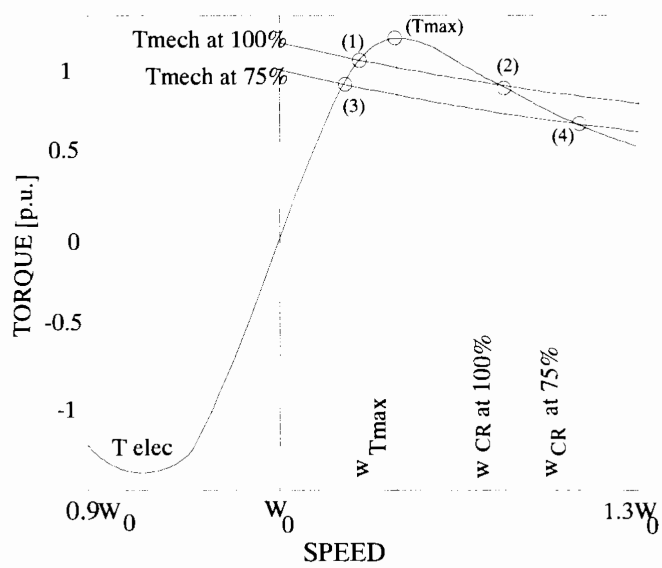


Figure 4.9: Torque versus speed characteristic of an induction generator, static (Tmax) and dynamic stability limits (2) and (4) [2]

The wind turbine torque, T_{mech}, is accelerating and the induction generator torque, T_{elec}, is decelerating. The wind turbine torque is given in two operational situations, i.e at 100% power production (the rated operation) and at 75% power production, respectively, which defines two different operational conditions for the wind turbine induction generator. If one would consider the case where the wind turbine is operating at 100% power production, then steady-state conditions are only possible on the two points (1) and (2) where the accelerating torque, T_{mech}, and the decelerating torque, T_{elec}, are equal. However, from these two points only point (1) is a stable operating point. The diagram illustrates that all possible steady-state generator operating points must be in the range from the synchronous speed, ω_0, to the max torque speed, ω_{Tmax}. The maximum torque speed therefore defines a static stability boundary for the induction generators. [2]

If a short circuit fault occurs on a grid where an induction generator is connected and the fault prevents the generator from feeding its active power into the grid, then the induction generator will accelerate. When the fault is cleared, the generator can only return to its normal operation if the generator speed does not exceed the critical value of speed, ω_{cr}, which corresponds to the point (2) on the graph at rated operation. If the critical speed, ω_{cr}, is exceeded, then the induction generator continues accelerating out of control and it will be necessary to disconnect the induction generator. The critical speed, ω_{cr}, is therefore the dynamic stability limit of the induction generator. If the induction generator is below its rated operation (i.e. 75% power production) in steady state, at point (3), another value of, ω_{cr}, is defined and this value corresponds to the point (4), which is another dynamic stability limit of the same generator.[2]

According to Akhmatov et al [2], the static stability of induction generators (in terms of exceeding the maximum torque speed) has been commonly applied for stability verifications but is not sufficient for the understanding of transient behaviours in electrical power systems with grid connected induction generators.

4.6.2 GENERATOR OVERSPEEDING AT FAULT

When using the per unit system, the movement equation of a induction generator is [2],

$$2H\frac{d\omega(t)}{dt} = T_{mech} - T_{elec} \qquad 4.6-1$$

Where H is the inertia constant of the generator rotor, and $\omega(t)$ is the time-dependent speed.

During equilibrium, the torque balance is maintained. The mechanical torque is equal to the electrical torque, and the generator speed is constant $\omega(t) = \omega_A$. When a short circuit fault occurs, the voltage on the terminals of the grid connected induction generator, V_s, falls. Since the electrical torque $T_{elec} \propto V_s$, it decreases exponentially with the characteristic time of the rotor transient τ. [2]

The mechanical torque is given equivalent to,

$$T_{mech}(\omega) = \frac{P_{mech}}{\omega(t)} \qquad 4.6-2$$

Where the mechanical power on the generator shaft, P_{mech}, may be considered constant. It is considered constant because the mechanical power is defined by the wind speed and the wind speed is considered constant during a time period of few seconds (in terms of short term stability). During a short circuit fault, the mechanical torque, T_{mech}, will decrease slightly due to an increase in generator speed $\omega(t)$.

Equilibrium between the opposing torques can only be achieved by accelerating the generator so that the speed of the generator is increased, as seen in Equation 4.6-1. Therefore when the speed of an induction generator increases during a short circuit fault, it does so because the mean value of the electric torque decreases much faster than the mechanical torque. When the short circuit fault is cleared, the electric torque has to be re-established. The characteristic time of this process is the characteristic time of the rotor transient, τ, analogously related to the electric torque during the failure time. Even if the short circuit fault is cleared, the generator speed continues to increase during the time of re-establishing of the electric torque. Equation 4.6-1 shows that the electric torque has to be larger than the mechanical torque for decelerating the generator to its original speed before the event of a failure, ω_A. If the electric torque is very low at the fault clearance time, and the condition $T_{elec} > T_{mech}$ cannot be fulfilled, the generator runs away and over speeding occurs. [2]

4.6.3 DYNAMIC STABILITY LIMIT OF INDUCTION GENERATORS

The dynamic stability limit of induction generators is determined by the maximum allowable speed $\omega(t)$, of the grid connected induction generator. The over speeding of an induction generator during a short circuit fault, should be limited to the critical speed, ω_{cr}, if the dynamic stability has to be maintained. The critical value of speed, ω_{cr}, is defined as the speed above the maximum torque-speed, ω_{Tmax}, when the electrical torque T_{elec}, is equal to the mechanical torque, T_{mech}.

$$T_{mech}(\omega) = T_{elec}(\omega) \qquad 4.6-3$$

The mechanical torque, T_{mech}, is given as a function of the induction generator speed, ω, as shown in Equation 4.6-3. The electric torque is usually given as a function of time, $T_{elec}(t)$. For the purpose of dynamic stability, the electric toque will be defined as a function of generator rotor speed, ω.

Akhmatov at al [2] define the electric torque versus speed characteristic of a grid connected induction generator as:

$$T_{elec}(\omega) = \frac{V_s^2(\omega)}{\omega} \frac{R_r(\omega)}{R_r^2(\omega) + X_r^2(w)} \qquad 4.6-4$$

Where the impedance viewed from the terminals into the induction generator is;

$$Z_r(\omega) = R_r(\omega) + jX_r(\omega) \qquad 4.6-5$$

$$R_r(\omega) = R_s + \frac{\frac{R_r}{\omega - 1} X_m{}^2}{\left(\frac{R_r}{\omega - 1}\right)^2 + (X_m + X_r)^2} \qquad 4.6-6$$

$$X_r(\omega) = X_s + \frac{X_m\left(\left(\frac{R_r}{\omega - 1}\right)^2 + X_R(X_m + X_r)\right)}{\left(\frac{R_r}{\omega - 1}\right)^2 + (X_m + X_r)^2} \qquad 4.6-7$$

Where R_r and R_s are the stator and rotor resistances, respectively, X_s, X_m and X_r, are the stator, magnetising and rotor reactances respectively, and the value (1- ω) gives the induction generator slip (negative for a generator operation).

The critical speed that determines the stability limit of the induction generators depends on the power supplied by the generators. The larger the electric power supplied by the generator, the lower the critical speed, and the lower the electric power supplied the higher the critical speed.

4.6.4 DYNAMIC STABILITY IMPROVEMENT

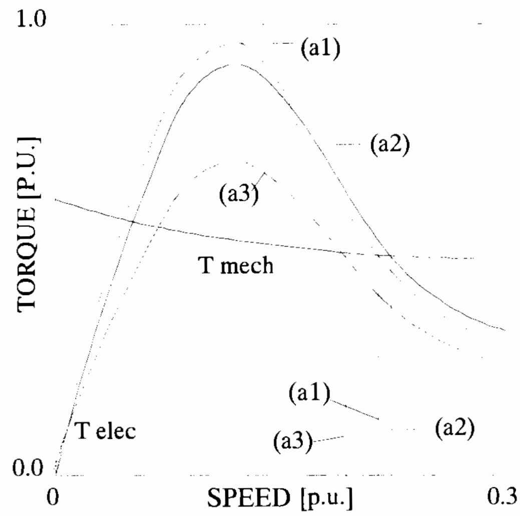
Voltage recovery versus collapse in a power grid with induction generators relates to the torque balance and over speeding of induction generators. Since the dynamic stability definition predicts that a distribution network with induction generators maintains its stability during a disturbance if the generator speed does not exceed the critical value, the dynamic stability of an induction generator can therefore be improved by increasing the critical speed. The possible ways this can be done is;[2]

- Increasing the electric torque at speeds above the maximum torque speed
- Reduction of electric torque during over speeding

4.6.4.1 Grid reinforcement and reactive power compensation

Grid reinforcement is the classical way of improving dynamic stability. It may be realised by building more overhead lines, tracking of cables, use of static or dynamic reactive power compensation. The results of this reinforcement will in terms of the dynamic stability definition, be seen as a reduction of the short circuit impedance of the electrical power grid that leads to; [2]

- A higher value of the terminal voltage, V_s, of grid connected induction generators and the tracing of more cables and overhead lines.
- A slower decrease of the terminal voltage with increase of the generator speeds above the maximum torque speed.
- These two arrangements result in the electric torque of grid connected induction generators, T_{elec}, and mechanical torque, T_{mech}, crossing at a higher value of speed, since $T_{elec}(\omega)\ \alpha\ V_s^2\ (\omega)$. This corresponds to a higher value of critical speed.



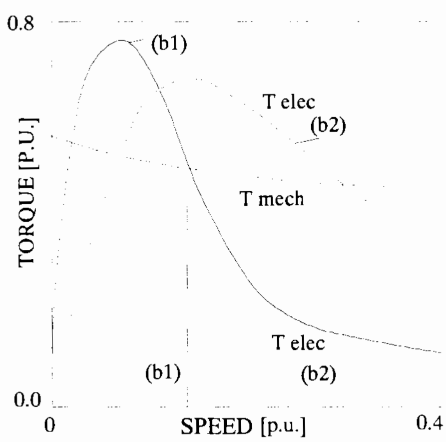
(a1) network reinforcements (a2) dynamic reactive compensation (a3) no reinforcement or compensation

Figure 4.10: Stability improvement in terms of dynamic stability limit definition: network reinforcement and dynamic reactive compensation [15]

The above graph illustrates these arguments, and from the point of view of the dynamic stability limit definition, network reinforcement leads to increasing of the critical speed of the grid connected induction machine. This leads to the improvement of the dynamic stability of the power system.

4.6.4.2 Generator parameters

Electrical and mechanical parameters of grid connected induction generators influence the dynamic stability of the power grid. The types of parameters include electrical parameters and generator inertia. [46]



(b1) unchanged value of rotor resistance (b2) 2X increased value of rotor resistance

Figure 4.11: Stability improvement in terms of dynamic stability limit definition: by generator data manipulation (increase of rotor resistance) [2]

<u>Electrical parameters</u>

For dynamic stability improvement, the resistance, R_r, has to be increased and the transient reactance has to be reduced. This will result in the critical speed increasing, as shown in figure 4.11. It also leads to a reduction in reactive power consumption by the induction generator. This exercise would make generators more costly because more time has to be taken to design generators with these specifications. A generator that has reduced transient reactance would have to be designed to have a shorter length. This design is practical however it would be very costly due to the unique design.

Stator resistance

The stator resistance also directly influences the dynamic stability of induction generators. This influence is however not significant because the stator resistances are typically small compared to the other impedance values in the induction generator. When large values of the stator resistance are used, they result in the worsening of dynamic stability.

Generator inertia

The higher the inertia constant, H, of a grid connected induction generator, the more stable the generator will be during post-fault operations. According to the dynamic stability limit definition, a small (light) and a large (heavy) induction generator have the same value of critical speed, ω_{cr}, if the electrical parameters are the same. The critical speed can be derived from the following equation,

$$T_{mech} = T_{elec} \qquad 4.6-8$$

If the inertia of an induction generator is to be increased, this would be achieved by increasing the diameter of the generator. This would result in the generator taking more time to accelerate after the occurrence of a large disturbance. Unfortunately this design would increase the manufacturing costs of the generator due to the large size.

Heavy induction generators are more stable at failure events of short duration because, according to equation 4.6-10 it takes more time to accelerate the heavy induction generator up to the critical speed than it will take for the light generator. Thus the critical clearing time will be larger for the heavy generator than for the small one. Large induction generators that are connected to the grid would hence be preferred over small generators. Large generators are however more expensive than smaller generators, and the total cost of connection is higher.

$$\omega_{cr(small)} = \omega_{cr(large)} \qquad 4.6-9$$

$$t_{cr(large)} \propto \sqrt{\frac{H_{large}}{H_{small}}} \cdot t_{cr(small)} \qquad 4.6-10$$

4.7 STABILITY PROPERTIES OF SYNCHRONOUS GENERATORS

Synchronous generators are extensively used because they allow the independent control of real and reactive power. They are rarely used to supply individual loads, but instead they are connected to a power grid. Synchronous generators consist of an armature winding and field winding. Normally, the field is on the rotor and the armature is on the stator. The field winding is excited by direct current. When the rotor is driven by a prime mover, the rotating magnetic field of the field winding induces alternating voltages on the three phase armature windings of the stator. The stator and the rotor fields react with each other and the electromagnetic torque opposes rotation of the rotor, so that the mechanical torque must be applied by the prime mover to sustain rotation. Changing the mechanical torque input by the prime mover changes the electrical torque output of the synchronous generator. The effect of increasing the mechanical torque input is to advance the rotor into a new position relative to the revolving magnetic field of the stator. Conversely, a reduction in mechanical torque or power input will retard the rotor position. During steady state operating conditions, the rotor field and the revolving field of the stator have the same speed. However, there is an angular separation between them depending on the electrical torque (or power) output of the generator.[31]

4.7.1 STABILITY CONSIDERATIONS

Equal area criterion demonstrates the conditions where synchronism is lost and pole slipping occurs. Figure 4.12 shows the power/load angle relationship and the rate of change of load angle (slip, S) for a generator losing synchronism with the utility to which it is connected following a loss of power transfer capability due to a disturbance on a double circuit line. For this scenario, the generator is connected to a double circuit line and the power system disturbance is caused by switching one of the lines out of service for a short period. Removing the electrical load from the generator while keeping the mechanical power constant causes the generator rotor to accelerate and eventually pole slip. The most severe disturbance for a generator is a close up three-phase fault, for which the entire load is lost and therefore all of the prime mover power is used to accelerate the rotor. For less severe short circuit faults, a greater fault duration is required to cause pole slipping. [43]

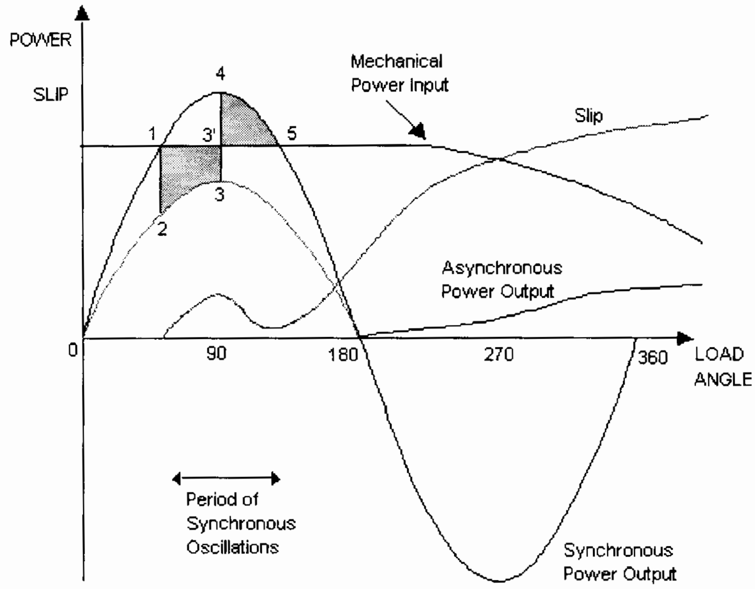


Figure 4.12: Equal area diagram for generator loss of synchronism [43]

Figure 4.12 shows that for a stable swing the machine operating point cannot exceed point 5, which is the critical stability point. Point 5 corresponds to the point at which the electrical power output of the generator, P, is equal to the mechanical input from the prime mover, P_m. If the generator happens to move beyond the critical stability limit (point 5) the generator will go into a state of instability.[43]

During the transient process the area 3'-4-5 when the machine is braking is smaller than the area 1-2-3-3' when it is accelerating. Thus the rotor, having passed the region 4-5 in which it is subject to braking forces, is accelerated again. The acceleration that begins at point 5, increases, and becomes appreciable when the load angle reaches 200-300°. With the increase of speed (and slip) the asynchronous torque and the power increase, causing the turbine regulators to reduce the mechanical power from the prime mover. [53]

4.7.2 SYNCHRONOUS GENERATOR DURING A DISTURBANCE

If the system is perturbed, the rotor of a synchronous generator accelerates or decelerates according to the laws of motion of a rotating body. If there are other synchronous generators connected onto the system and one synchronous generator runs faster than the others, the angular position of the rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This will result in the reduction of the speed difference and hence the angular separation. The power-angle relationship is highly non-linear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer. This increases the angular separation further and leads to instability. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques. [31]

Transient disturbances are a threat to the stability of synchronous generators because they can result in the loss of synchronism between the synchronous machine and the supply to which it is connected. This causes the distributed generator to pole slip with respect to the utility grid supply. If a power system fault persists beyond a certain length of time, the synchronous generator will inevitably swing out of synchronism. The pole slipping is accompanied by dramatic fluctuations in currents both absorbed and provided by the generator.

4.8 DESCRIPTION OF DIGSILENT POWER FACTORY SOFTWA

Digsilent power factory software is the simulating software that is used to carry out transient and voltage stability studies in subsequent chapters. This software was found to be the most suitable software in terms to of price, functionality and technical support.

Digsilent Power Factory 12.1 software is an integrated power system analysis tool, and is used to carry out the stability studies in subsequent chapters. The software has been developed on the basis of algorithms and models from the Digsilent version 10.31, using the new object oriented software technology with C++.

The software package allows studies to be done on power system generation, distribution and generation networks. Due to the modelling capabilities, there is no need to apply different software packages for the various categories of power system applications such as generation, distribution and transmission. Digsilent handles AC/DC power flow, VDE/IEC fault analysis, dynamic simulations (RMS), EMT Simulation, Relay coordination and other features. [9]

There is no fixed dimension given for the maximum program capacity. Since the program automatically allocates the required memory, the large-scale version of Digsilent is not configured for a fixed maximum number of substations. User needs and hardware restrictions are the only limitations. However there are bus number limitations, defined according to the various price categories. The package that was used in this research was limited to 35 bus-bars.

4.9 SUMMARY

Theoretical stability aspects of distributed generation are presented in preparation for the stability studies that will be conducted in subsequent chapters. The stability concepts as well as stability definitions have been clarified. The forms of stability that need to be investigated further have been identified, which include transient and voltage stability. These forms of stability need to be investigated further because after the occurrence of a severe disturbance on a distribution network connected with DG, depending on the type of machinery the DG utilises, there is a threat of voltage and transient stability.

In preparation for the stability studies network models, generator models, load models and disturbances used in case studies were covered. The dominant type of distribution network topology that will be used in the case studies is the radial distribution network, as it is dominantly found in Southern Africa. The generator models from Digsilent are also presented since they are used to represent distributed generators in the stability studies. A load model from Digsilent is also presented, which was found to be capable of modelling a mixture of static and dynamic loads that are required to represent residential, industrial and commercial loads. Three phase faults were identified as the type of disturbance that would be appropriately used to simulate severe transient disturbances that threaten the stability of distributed generators.

Distributed generators were found to be generally characterised by low inertias, high per unit reactances, short transient time constants and poor inherent damping. The general characteristics greatly impact the stability of DGs because they result in low generator critical fault clearing times (CCT).

Electriy weak distribution networks that are typically found in Southern Africa contribute to the increased possibility of instability on distribution networks. With induction generators connected to a weak distribution network, there is a possibility of voltage instability after the occurrence of a severe transient disturbance.

After presenting this chapter the stability of distribution networks that are connected with distributed generation can be summarised and classified into a diagram similar to Figure 4.13

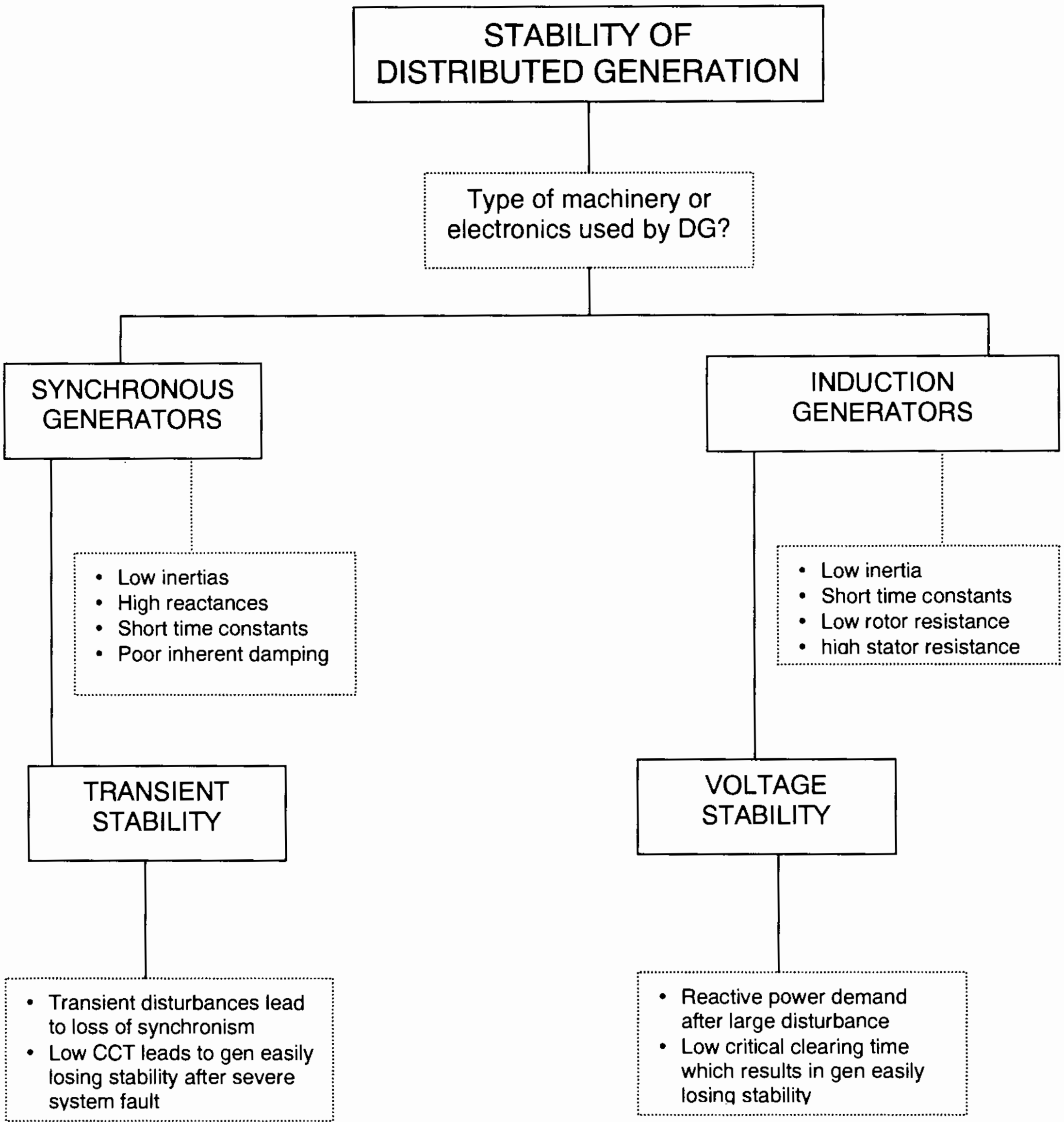


Figure 4.13: Classification of stability of DG

CHAPTER 5

TRANSIENT STABILITY SIMULATIONS AND ANALYSIS

This chapter presents transient stability studies that were carried out in order to highlight transient stability issues that are raised when distributed generators are connected to distribution networks. These stability studies were carried out on existing distribution networks that are connected with distributed generation, as well as model non-actual systems. This chapter seeks to investigate the conditions that lead to transient instability and investigate the impact of generator parameters on transient stability. As justified in chapter 3, only two types of distributed generation technologies are investigated, these include wind turbines and hydro turbines. These technologies represent different conventional electrical machines. Since the characteristics of technologies using similar machines are comparable, it is not imperative to include all technologies in the stability investigations. Stability studies have been conducted by separating different studies into case studies. Case studies were selected in order to investigate various cases of stability to identify limiting factors where DG is connected to weak distribution systems typical of Africa. The systems that will be studied in this chapter include;

- A 'typical' small network with wind and hydro DG connected to a 11kV grid,
- A portion of the Mbabane distribution system with a hydro generator

The 'typical' small network is a non-actual system and does not exist. It was modelled as a 11kV network connected with wind and hydro generators. The 'typical' small network was designed in order to highlight transient stability issues that are raised when DG is connected to the distribution network.

The Mbabane distribution system exists in Swaziland, and was identified in Table 2.6.The Mbabane distribution system was selected because it is an existing example of DG in Southern Africa. The Mbabane network only has one generator, and it is an ideal network to investigate how the generator parameters affect the transient stability because there is no interference from other generators connected to the grid.

This chapter contains four sections. The first section introduces transient stability analysis of generators that are connected to the network. The next section is the first case study that investigates how the fault location and the load condition on a distribution network affect the critical fault clearing time of a synchronous generator. The third section is the second case study that investigates the impact of synchronous generator parameters on transient stability. The final section presents a summary of the chapter.

5.1 TRANSIENT STABILITY ANALYSIS

Transient stability is concerned with the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The objective of transient stability studies is to determine whether the machines will return to synchronous frequencies with new steady state power angles after being subjected to a large disturbance. In order to assess the transient stability of a synchronous generator the critical fault clearing time (CCT) of the generator has to be established. The CCT indicates the fault duration that just avoids the synchronous machine pole slipping and losing stability. When an asynchronous generator is connected to a distribution network and a transient disturbance occurs, transient stability would be concerned with the ability of the asynchronous machine to maintain rotor speeds that would not lead to the generator not being able to return to the rated rotor speed when subjected to a transient disturbance. [7]

The different aspects that will be investigated in this chapter include;

- Critical fault clearing time (CCT) of a synchronous generator
- Impact of fault location on CCT of a synchronous generator
- Impact of distribution network load condition on CCT of a synchronous generator
- Impact of parameters of a synchronous generator on transient stability

5.2 CASE STUDY 1 - Typical Southern African Radial Distribution Network

The system in this case study is not an actual system, but has been chosen to investigate key stability issues that are raised by the connection of DG units on a distribution network. Case study 1 was the initial case study that was looked at, therefore a simple distribution network layout was designed. This is a typical distribution network that would be found in non-urban areas of

Southern Africa. Stability investigation on these types of networks would therefore reveal stability issues that are raised when electrically weak radial distribution networks are connected with DG.

This case study seeks to investigate how the fault location and the load condition on a distribution network affects the critical fault clearing time. Some general concepts have already been covered in chapter 4, but the case study will prove whether these concepts apply to a case where a distributed generator is connected to a distribution network.

5.2.1 NETWORK DESCRIPTION

The distribution network consists of 6 bus bars, 2 transformers, 9 lines and 3 voltage levels. The network represents an electrically weak radial distribution network, which is typically found in rural areas in Southern Africa. All the loads and the generators are connected to the 11kV feeders. The distances of these feeders were varied in order to create a variety of lengths. This was done in order to change the impedance of the feeders. The grid connection point is on the 132kV bus bar. The line conductor that was used for all the distribution lines is 63mm ACSR (Aluminium Conductor Steel Reinforced). This type of conductor is widely used in Southern Africa, especially on 11kV feeders.

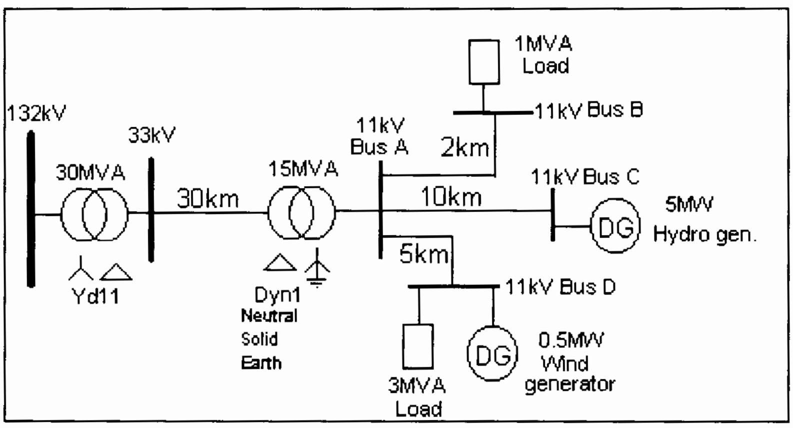


Figure 5.1: Case study 1 distribution network diagram

5.2.2 GENERATORS

A 5MW synchronous hydro-generator as well as a 0.5MW induction wind generator were the distributed generators that were selected. These generators were selected because the full generator data was made available to the author, and they represented the two different types of electric machines. The generator data for these machines is listed in Appendix A. The governor and exciter models are presented in Appendix G.

5.2.3 LOAD MODEL

The load model that was selected was a mixture of static and dynamic loads. The load model represents residential, commercial and industrial loads all in one model. Sub-section 4.3.3 covered the theory on the load model that was used in the simulations.

The types of loads modelled include a balanced 1MVA and 3MVA load, with power factors of 0.85. Sixty-percent of the load model was static (constant Z) and the forty-percent was dynamic. These are the typical proportions that would be used to represent a Southern African residential, commercial and industrial load.

5.2.4 DISTURBANCE

Because the most severe disturbance threatening the transient stability of a synchronous generator is a three-phase fault, three-phase faults were imposed on the different locations of the network to simulate large disturbances. The introduction of three phase faults was the only form of disturbance imposed onto the network because it is one of the most effective methods of introducing transient disturbances on a network. The three-phase fault current at the location where the fault occurred was recorded, in order to assist in the analysis.

5.2.5 LOAD FLOW STUDY

A load flow diagram of case study 1 is shown in Appendix A. The load flow results of the network show that the hydro generator is not able to supply the reactive power required by the network lines, induction generator and the loads. Reactive power is hence imported from the external grid. There is however excess active power, which is exported to the external grid. The steady state voltage levels on all the bus bars are within 10% of the nominal values. The hydro generator controls 11kV Bus C voltage and keeps it at 11kV. The load flow results indicate that under normal conditions the network is stable.

5.2.6 SIMULATION

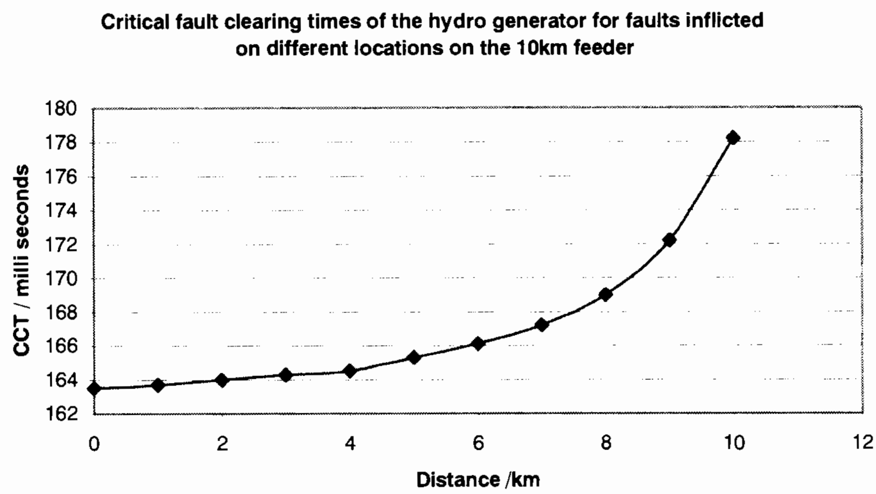
The simulation was divided into four parts. The first three parts were for the investigation on the impact of fault location on the transient stability of distributed generators, and the final part investigated the impact of distribution network load on the transient stability of a DG. The first part examined the critical fault clearing time (CCT) of the synchronous generators at different locations on the 10km feeder to which the DG is connected. The second part examined the CCT of the synchronous generator when the transient disturbances occurred on the 2km lateral feeder. The third part examined the CCT of the synchronous generator when a transient disturbance was introduced on another longer lateral 5km feeder that was connected with an induction generator. The fourth and final part examined the CCT of the synchronous generator after load on the distribution network was increased.

The CCT was established by monitoring the rotor angle of the hydro generator. When the rotor angle moved rapidly between +/-180°, the generator would have lost synchronism. Therefore a fault duration that would just avoid the rotor angle from rapidly and endlessly moving between +/-180° would be recorded as the CCT. The speed signals, turbine power and the excitation voltage were also monitored during the simulation.

RESULTS OF IMPACT OF FAULT LOCATION ON TRANSIENT STABILITY (10km feeder)

Distance / km	CCT /milli seconds	Fault current
0	163.5	3.608
1	163.7	3.26
2	164	3.024
3	164.3	2.866
4	164.5	2.787
5	165.3	2.717
6	166.1	2.710
7	167.2	2.745
8	169	2.826
9	172.2	2.962
10	178.2	3.168

Table 5.1: Results for critical fault clearing times and fault current on the 10km feeder
** 0km corresponds to 11kV Bus A*



* *0km corresponds to the 11kV Bus A*

Figure 5.2: Critical fault clearing times of the hydro generator for the occurrence of faults on the 10km feeder

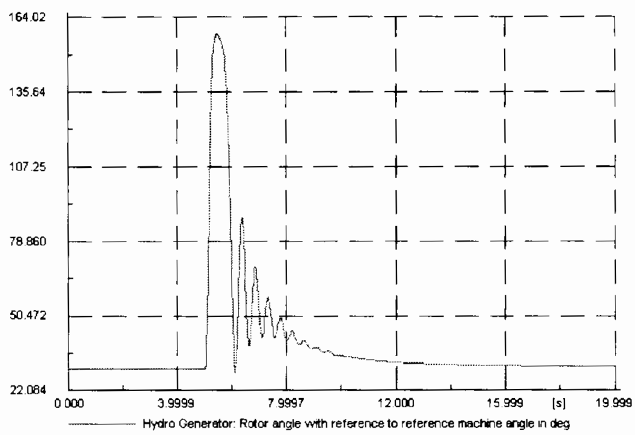


Figure 5.3: Rotor angle response after a 178.2msec fault on the hydro generator terminals

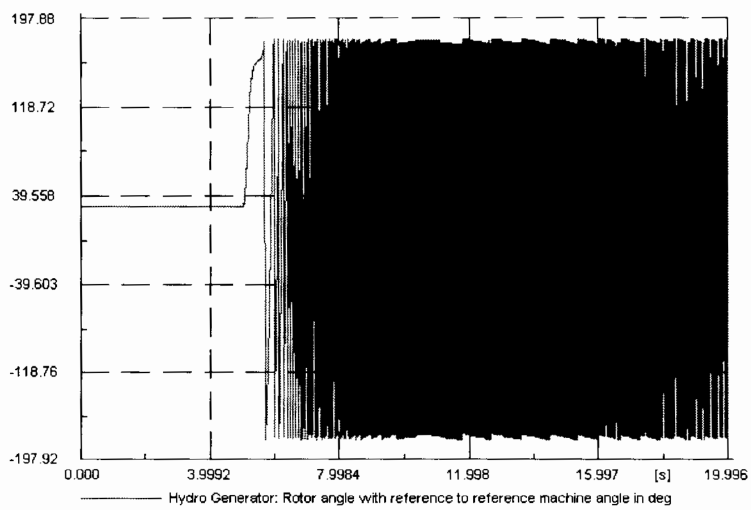


Figure 5.4: Rotor angle response after a 178.3msec fault on the hydro generator terminals

The simulations done in this section were investigating the impact of fault location on the transient stability of a distributed generator. The results above indicate that when a three-phase fault is inflicted on the feeder to which the synchronous hydro generator is connected, the closer the disturbance is to the generator the larger the critical fault clearing time (CCT). And the further a large disturbance is from the synchronous generator the smaller the CCT. The relationship of critical fault clearing time against distance is non-linear as shown in Figure 5.2. This result was not expected, but instead is the opposite of what was expected. The result that was expected is the closer a large disturbance is to a synchronous generator the smaller the CCT, and the further a large disturbance is to a synchronous machine the larger the CCT. This possibly happens because there is a higher fault current on the 11kV bus A than the bus bar to which the generator is connected. The CCT on the 10km feeder ranges from 163.5 – 178.2milli-seconds. Even though the relationship shown in Figure 5.2 is non-linear the CCT difference between the two feeder end points is only 14.7milli-seconds.

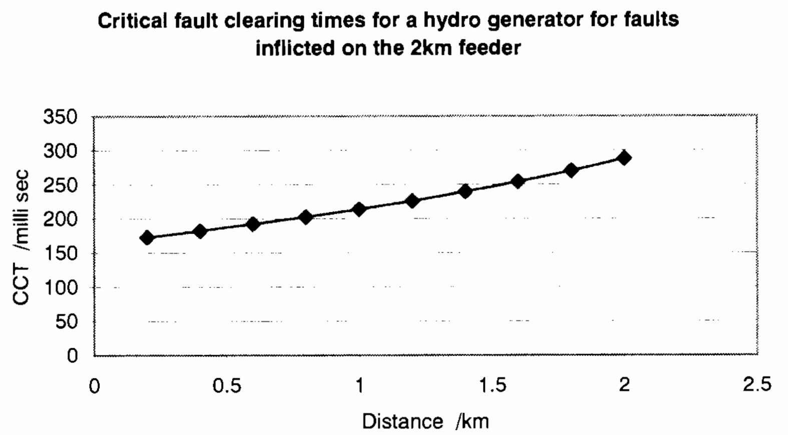
The results of the fault current for the different fault locations are listed in Table 5.1. The fault current changes due to the change in fault impedance at the different fault positions on the feeder. The Table indicates that the higher the fault current the smaller the critical clearing time, and the smaller the fault current the larger the CCT. It should be however noted that the fault current is the three-phase fault current that would flow at the location of the fault. Figure 5.3 captures the response of the rotor angle after a 178.2msec fault on the hydro generator terminals. This is the maximum fault duration before the generator loses synchronism. It is visible that the rotor angle shoots as far as approximately 160 degrees, which is very close to the limit of 180 degrees. After a fault duration of 178.3msec, the synchronous generator pole slips and goes into a state of transient instability. Figure 5.4 captures the response of the rotor angle when the generator loses its stability. It is visible that the rotor angle moves rapidly between +/-180 degrees.

RESULTS OF IMPACT OF FAULT LOCATION ON TRANSIENT STABILITY (2km feeder)

Distance / km	CCT /milli seconds	Fault current /kA
0	163.5	3.608
0.2	172.6	3.446
0.4	182	3.229
0.6	192	3.163
0.8	202.5	3.038
1	213.8	2.922
1.2	225.9	2.815
1.4	239	2.716
1.6	253.5	2.623
1.8	269.5	2.536
2	287.7	2.455

Table 5.2: Results for critical fault clearing times and fault current on the 2km feeder

** 0km corresponds to 11kV Bus A*



* *0km corresponds to the 11kV Bus A*

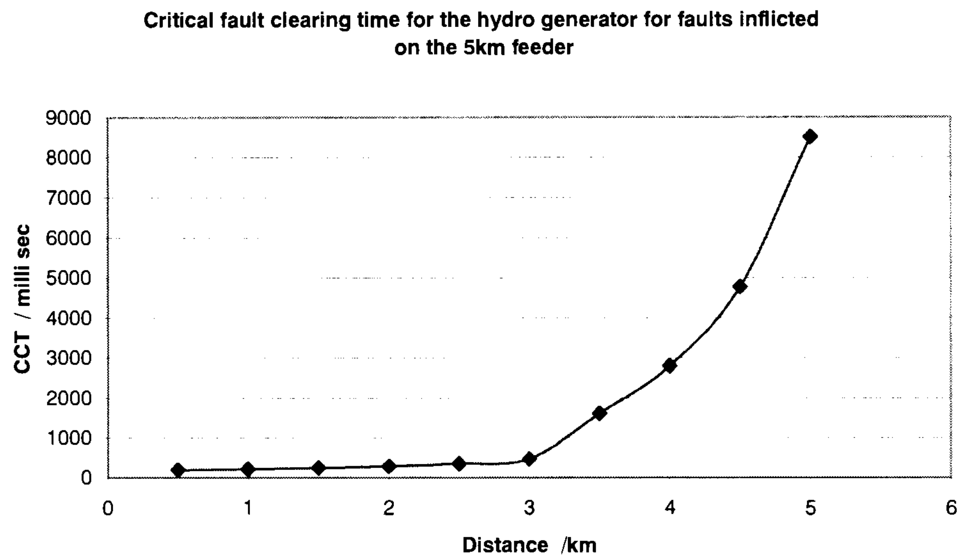
Figure 5.5: Critical fault clearing times of the hydro generator for the occurrence of faults on the 2km feeder

The simulations done in this section were investigating the impact of fault location on the transient stability of distributed generators. The 2km feeder is different from the 10km feeder because it is a lateral feeder. The results on the lateral 2km feeder indicate that the closer a large disturbance is to the hydro generator the smaller the critical fault clearing time (CCT), and the further a large disturbance is from the hydro generator the larger the CCT. This result was expected because it is in agreement with the theory. The relationship of the CCT against distance away from the 2km feeder (Figure 5.5) is very close to being linear. However this might be caused by the fact that the feeder is short. The critical fault clearing times on this feeder are observed to be reaching figures that are almost double the figures recorded on the 10km feeder. The maximum value of CCT recorded on the 2km feeder was 287.7 milli-seconds, this duration is still relatively short when compared to the speeds at which protection devices respond on a typical distribution network. Table 5.2 also shows that the higher the fault current the shorter the CCT.

RESULTS OF IMPACT OF FAULT LOCATION ON TRANSIENT STABILITY (5km feeder)

Distance / km	CCT /milli seconds	Fault current /kA
0	163.5	3.608
0.5	187	3.26
1.0	213.9	2.976
1.5	246.2	2.74
2.0	288	2.541
2.5	349.2	2.37
3.0	468	2.222
3.5	1604.9	2.093
4.0	2795.5	1.98
4.5	4771.2	1.879
5.0	8501.3	1.789

Table 5.3: Results for critical fault clearing times and fault current on the 5km feeder
* *0km corresponds to 11kV Bus A*



* *0km corresponds to the 11kV Bus A*

Figure 5.6: Critical fault clearing times of the hydro generator for the occurrence of faults on the 5km feeder

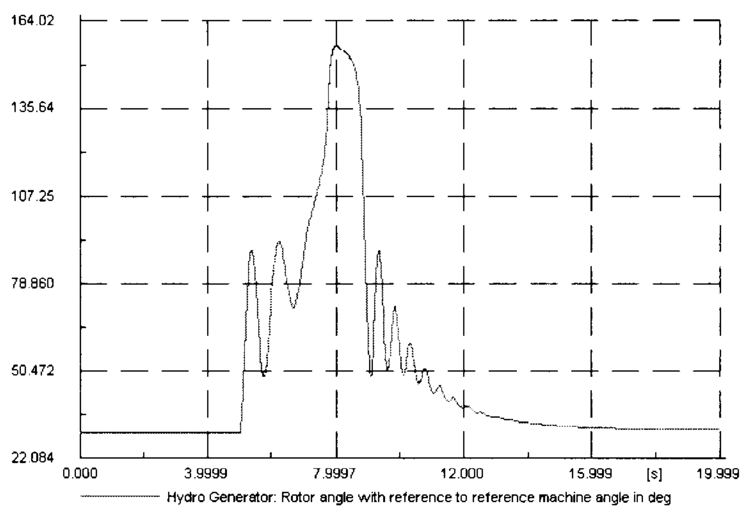


Figure 5.7: Rotor angle response after a 2795.5 msec fault on the 5km feeder (4km away from the 11kV bus A)

The simulations done in this section were still investigating the impact of fault location on the transient stability of distributed generators. The 5km feeder has a higher impedance than the 2km feeder, and a wind generator is connected to it. The CCT results on the 5 km lateral feeder increased as the distance away from the hydro generator was increased. This was expected as reviewed in the literature survey. There were extremely high CCT values that were recorded from the middle of the 5km feeder to the end of the feeder. These results are too high for critical fault clearing times. Because they are too high, this means the fault duration is no longer critical sinc e almost all protection devices would be able to clear such a long duration fault. As shown in Figure

5.6, the relationship between CCT against distance from 11kV bus bar A is non-linear and almost exponential. The large values of CCT were possibly caused by the influence of the rigid external grid. When the length of a lateral feeder is increased beyond 3km from 11kV bus A, the CCT values of the synchronous generator increase at a high rate. Table 5.3 also indicates that the higher the fault current the smaller the critical clearing time, and the smaller the fault current the larger the CCT. The fault current however does not drop at an alarming rate beyond 3km from 11kV bus A, but drops at a constant rate.

Figure 5.7 captures the rotor angle response after the occurrence of a 2.8sec fault on the 5 km feeder (4km away from 11kV bus bar A). This is the maximum duration that would not lead to the hydro generator losing its stability. The synchronous generator fully recovers from the fault in +/- 12 seconds, and returns relatively close to its pre-disturbance rotor angle. When Figure 5.7 is compared to Figure 5.3, it is clear that they do not have a similar profile.

RESULTS OF IMPACT OF NETWORK LOAD ON TRANSIENT STABILITY (2km feeder)

Load /MVA	CCT /msec
0.2	214.5
0.4	214.3
0.6	214.1
0.8	213.9
1.0	213.8
1.5	213.3
2.0	212.8
2.5	212.4
3.5	211.4
5	210
7	208.1
10	205.3

Table 5.4: Results for critical fault clearing times for different load values on the 2km feeder after a 3 phase fault in the middle of the 2km feeder

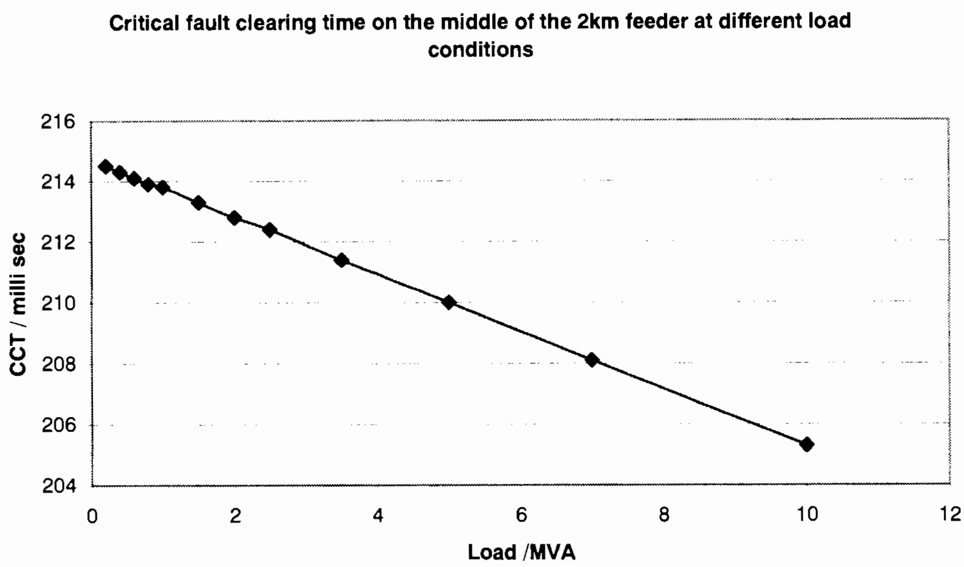


Figure 5.8: Critical fault clearing times of the hydro generator for an increase in load on the 2km feeder

The simulations done in this section were investigating the effect of a distribution network load increase on the transient stability of a distributed generator. The results from Figure 5.8 indicate that the larger the load the lower the critical fault clearing time, therefore the more critical the fault will be towards the synchronous generator stability. This relationship was expected because when there is a larger load the network will be stressed (due to increased currents flowing) increasingly and would quickly go into a state of instability. The relationship shown in Figure 5.8 is very close to being a linear relationship. It is however worth noting that for a fifty times increase in load the critical fault clearing time only decreases by 5 %.

5.2.7 ANALYSIS OF RESULTS

The results show that the closer a large disturbance is to a synchronous generator the shorter the critical fault clearing time, and the further away a large disturbance is from a synchronous generator the longer the critical fault clearing time. This result was expected, however a different result was obtained on the feeder to which the synchronous generator was connected. This strange result could have been caused by the fact that there was a higher fault current on the 11kV bus bar A.

When the disturbance occurs on lateral feeders, as you move away from the synchronous generator the critical fault clearing time also increases. This result supported the expectations. The CCT results on the 5km feeder were discovered to be higher than expected. The reason for this could be due to the influence of the rigid external grid. In order to investigate this irregularity lateral feeders not directly connecting the synchronous machine to the central system were critical when they are close to the 11kV bus A (connected to the 15MVA transformer).

The relationships of CCT against distance were found to be non-linear, therefore meaning that the further a fault is to the synchronous generator the less critical it is. This study demonstrates that the fault current is inversely proportional to the critical fault clearing time. To a certain degree the fault current can indicate how critical a fault can be to the stability of the distributed generator. When the load that is being supplied by the generator increases the critical fault clearing time decreases linearly. Therefore if a large disturbance occurs during peak load there is a higher possibility that the generators that are connected onto the network will lose their stability, depending on the fault location.

5.3 CASE STUDY 2 - Portion of Mbabane 11kV Network

The system chosen in this case study exists in Swaziland near the city of Mbabane, and was identified in Table 2.6 in chapter 2. This case study shows a typical existing example of distributed generation in Southern Africa, because a generator is connected to a distribution voltage level (11kV) and is embedded within the distribution network. Only a potion of the network has been simulated and the network has been simplified, therefore some areas have been lumped into a single load. This was done in order to simplify the network. However the backbone of the existing network has not been altered. On this system a hydro generator is connected to a 11kV distribution system. This hydro station was commissioned in 1953 when the electricity industry was still run by the government in Swaziland. The generator was commissioned in order to mainly supply electricity to the British High Commission, and a few other consumers. When Swaziland Electricity Board became a parastatal in 1963, it took control of the hydro generator. Accurate electrical data of the hydro generator was not available, and according to Swaziland Electricity Board, when they took over the generator no records of the generator were handed over to them. The parameters that were used in this study were estimated using data from similar sized synchronous generators.

This case study seeks to investigate how different parameters of a synchronous generator impact the transient stability of the distribution network that is connected with DG. The different generator parameters that are investigated include the synchronous reactance (Xd), the transient reactance (Xd'), the sub-transient reactance (Xd") and the Inertia constant (H). Since the Mbabane network only has one generator, it is an ideal network to investigate how the generator parameters affect the transient stability because there is no interference from other generators connected.

5.3.1 NETWORK DESCRIPTION

The distribution network consists of 14 bus bars, 6 transformers, 13 lines and 2 voltage levels. The distribution network exists in an urban area, and it is a ring network. The distribution network is a 11kV network, which is a typical distribution voltage level in Southern African urban areas. All the loads are connected to a voltage level of 400V. On the original network the distribution transformers range from 15kVA to 315kVA, and the consumers that are connected are mainly residential and commercial consumers, and a few industrial consumers. There are two grid connection points that increase the reliability of the network. The line conductor that was used for the distribution lines is a 63mm ACSR (Aluminium Conductor Steel reinforced) cable, which is the existing distribution line on the Mbabane Network.

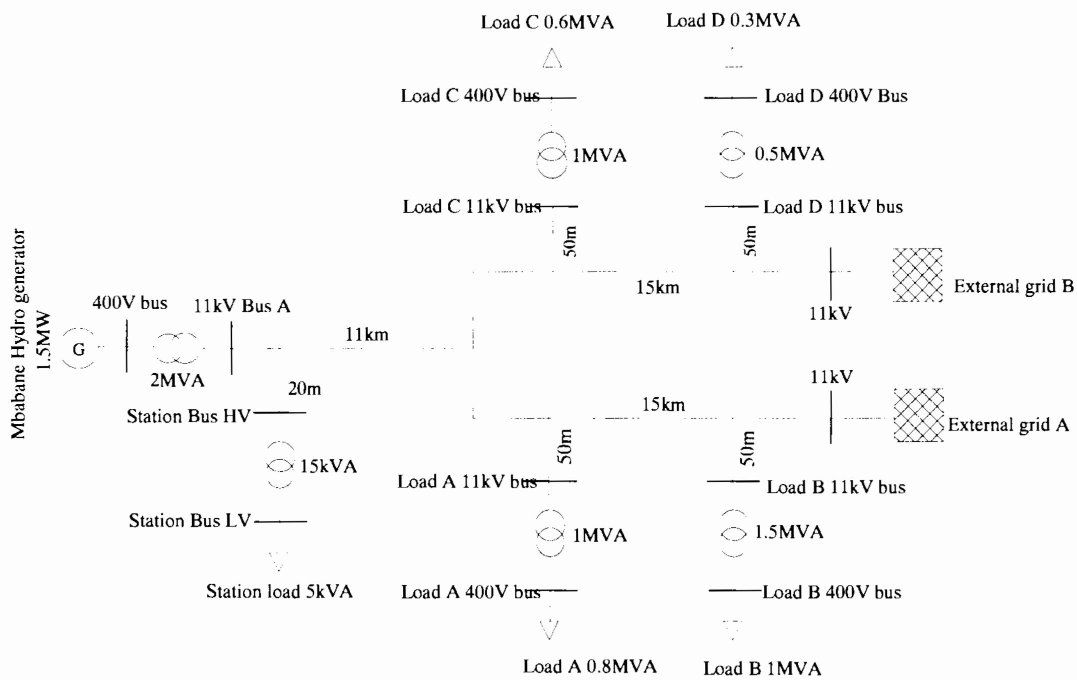


Figure 5.9: Single line diagram of a portion of the Mbabane network

5.3.2 GENERATOR

A 1.5MW synchronous hydro generator is the embedded generator in the distribution network. As listed in Table 2.6, the generator is very old since its commissioning year was in 1953. Even though the generator is very old it still generates power onto the Mbabane network. This generator has a voltage controller as well as a governor connected. The estimated generator data for this machine is listed in Appendix B. The governor and exciter models as well as their parameters are also listed in the appendix. The governor and exciter models are not the exact ones that exist at the hydro station.

5.3.3 LOAD MODEL

The load model that is utilised on the distribution network is a mixture of static and dynamic loads. The load model represents residential and commercial loads all in one model. Sub-section 4.3.3 covered the theory on the load model that was used in the simulations.

The loads modelled include balanced 0.3MVA, 0.6MVA, 0.8MVA and 1MVA loads, with power factors of 0.85. Sixty-five percent of the load model was static (constant Z) and thirty-five percent was dynamic. Industrial loads are not modelled because they do not exist on this portion of the network. For this reason only thirty-five percent of the load model was modelled as dynamic.

5.3.4 DISTURBANCE

The type of disturbance that was inflicted on the distribution network is a three-phase fault. In this case study it was inflicted on the terminals of the hydro generator. This is one of the most severe faults that could occur to the synchronous generator, and it threatens the transient stability of the hydro generator.

5.3.5 LOAD FLOW STUDY

A load flow diagram of case study 2 is shown in Appendix B. The load flow results of the network show that active and reactive power is imported from external grid A and external grid B. The Mbabane hydro generator assists by injecting some active and reactive power to the network, however this is not enough to supply the demand of the network. The steady state voltage levels on all the bus bars are close to their nominal values. The load flow results indicate that under normal conditions the network is stable.

5.3.6 SIMULATION

The simulation was divided into five parts. The first four parts examined the impact of synchronous generator parameters on transient stability. The different parameters that were investigated included synchronous reactance (Xd), transient reactance (Xd'), sub-transient reactance (Xd") and inertia constant (H) of the synchronous generator. The fifth and final part examined the impact of generator loading on transient stability

A three-phase fault was inflicted on the terminals of the synchronous generator and the critical fault clearing time (CCT) was determined. The value of the parameter (e.g. H, Xd, Xd', Xd") that was being investigated was then varied and the other parameters were kept the constant. While varying the parameter that was being investigated the CCT was determined. When investigating the generator loading, the synchronous generator power production set-point was fixed at various levels, and then the CCT was determined. The critical fault clearing time was determined by monitoring the rotor angle of the hydro generator. When the rotor angle moved rapidly between +/-180°, the generator would have lost synchronism. A fault duration that would just avoid the rotor angle from rapidly and endlessly moving between +/-180° would be recorded as the CCT.

EFFECT OF SYNCHRONOUS REACTANCE ON TRANSIENT STABILITY

Synchronous reactance (Xd) / p.u.	CCT / milli seconds
0.8	219
0.85	218.7
0.9	218.5
0.95	218.3
1.0	218.1
1.05	218
1.1	217.8

Table 5.5: Results of the effect of synchronous reactance on CCT

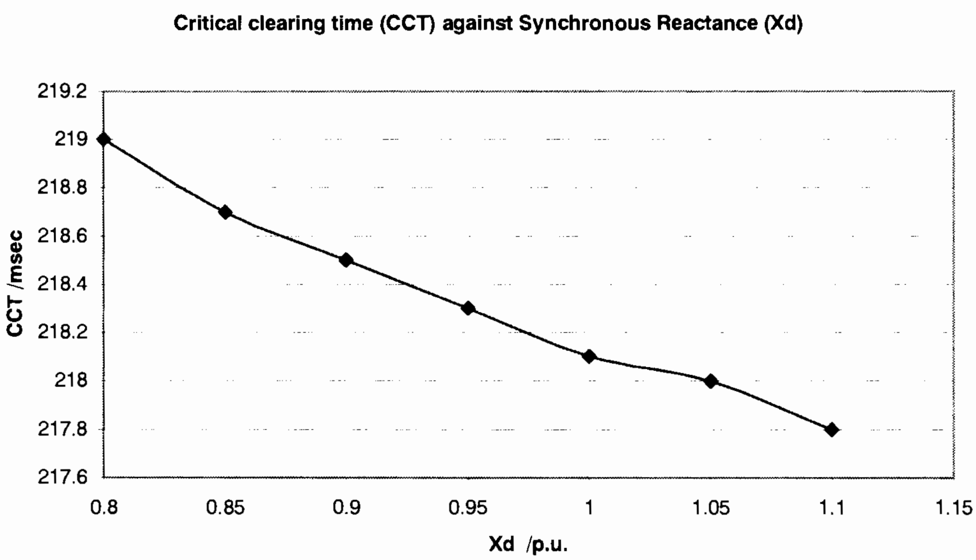


Figure 5.10: Effect of synchronous reactance on the critical fault clearing time

The results above indicate that the higher the synchronous reactance the lower the critical fault clearing time, therefore the more critical it is. It would therefore be suitable to have synchronous distributed generators that have synchronous reactances that are as low as possible. The relationship between CCT against synchronous reactance (Xd) that is illustrated in Figure 5.10 is close to being linear. This result was expected, but the magnitude of influence was not known.

For a thirty-seven percent increase in Xd, the CCT dropped by half a percent, which is quite low considering the fact that synchronous reactances have a very limited range.

EFFECT OF TRANSIENT REACTANCE ON TRANSIENT STABILITY

Transient reactance (Xd') / p.u.	CCT / milli seconds
0.15	249
0.22	224
0.25	218
0.3	209
0.35	202
0.4	197
0.45	190

Table 5.6: Results of the effect of transient reactance on the CCT

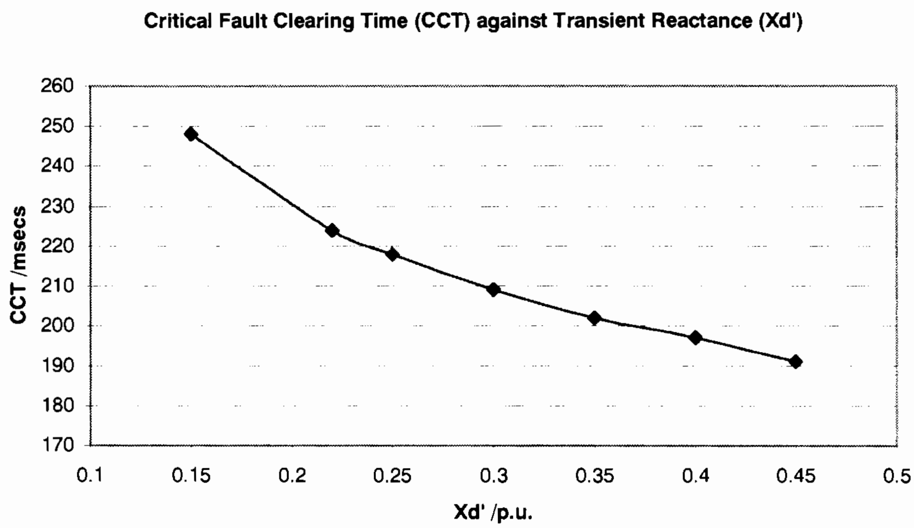


Figure 5.11: Effect of transient reactance on the critical fault clearing time

Figure 5.11 shows that for an increase in the transient reactance (Xd') the critical fault clearing time decreases, and for a decrease in transient reactance, the CCT increases. This relationship between CCT against Xd' is not linear, but close to being linear. For a two hundred percent increase in transient reactance the critical fault clearing time decreased by almost twenty-five percent, which is quite significant. This result shows that the transient reactance can greatly affect the critical fault clearing time of the distributed generator.

EFFECT OF SUB-TRANSIENT REACTANCE ON TRANSIENT STABILITY

Sub-transient reactance (Xd") / p.u.	CCT / milli-seconds
0.19	226
0.22	218
0.25	215
0.3	212
0.35	210
0.4	198

Table 5.7: Results of the effect of sub-transient reactance on the CCT

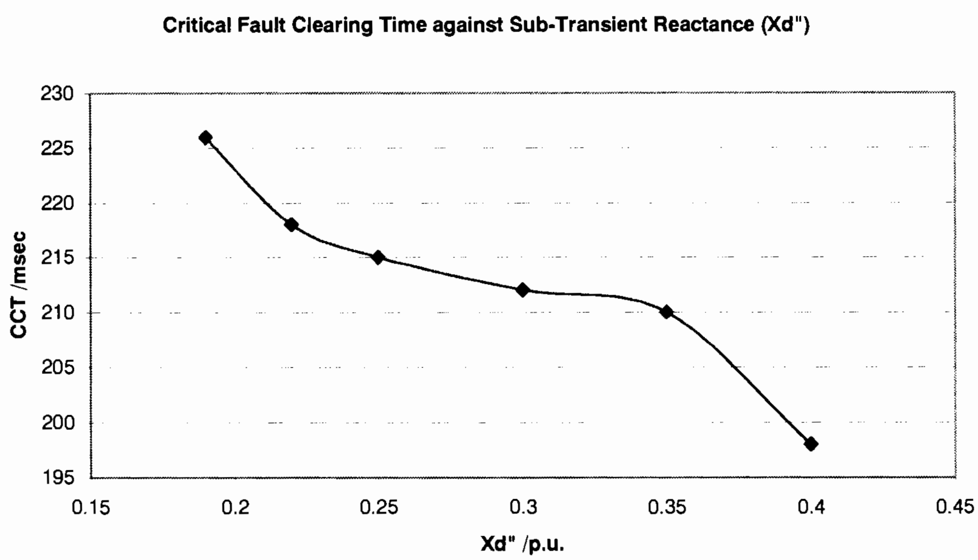


Figure 5.12: Effect of sub-transient reactance on the critical fault clearing time

The graph in Figure 5.12 confirms that an increase in sub-transient reactance (Xd") results in a decrease in critical fault clearing time. And a decrease in (Xd") results in an increase in the CCT. The relationship shown in Figure 5.11 of CCT against Xd" is definitely non-linear. A 110% increase in sub-transient reactance resulted in a 12% decrease in CCT.

EFFECT OF INERTIA CONSTANT ON TRANSIENT STABILITY

Inertia Constant (H) / seconds	CCT / milli-seconds
0.4	119
0.6	144
0.8	165
1.0	184
1.2	200
1.43	218
1.6	230
1.8	243
2.0	255
2.2	267
2.4	278
2.6	289
2.8	299
3.0	309
3.2	319
3.4	328
3.6	337
3.8	346

Table 5.8: Results of the effect of the inertia constant on the CCT

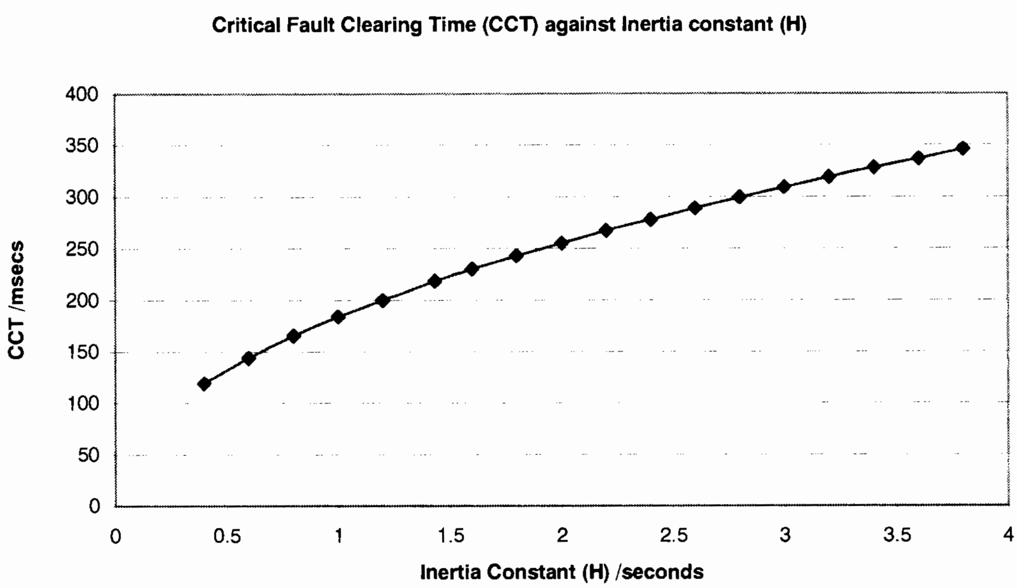


Figure 5.13: Effect of inertia constant on the critical fault clearing time

The results above indicate that the inertia constant of a generator can impact the critical fault clearing time of a synchronous generator. An increase in inertia constant (H) results in an increase in the critical fault clearing time. This relationship which is illustrated in Figure 5.13 is non linear, and the rate of increase decreases as the inertia constant increases. This result was expected as mentioned in the literature survey, however the magnitude of impact was unknown.

An 850% increase in the inertia constant resulted in a 190% increase in CCT, which is quite significant. As mentioned in chapter 3 distributed generators generally have low inertia constants because an increase in inertia constant results in a increase in cost, this property causes stability concerns because this results in the DG units having low critical fault clearing times.

EFFECT OF GENERATOR LOADING ON TRANSIENT STABILITY

Power production / %	CCT /msec
40	375
50	315
60	273
70	242
80	218
90	198
100	183

Table 5.9: Results of the effect of the generator loading on the CCT

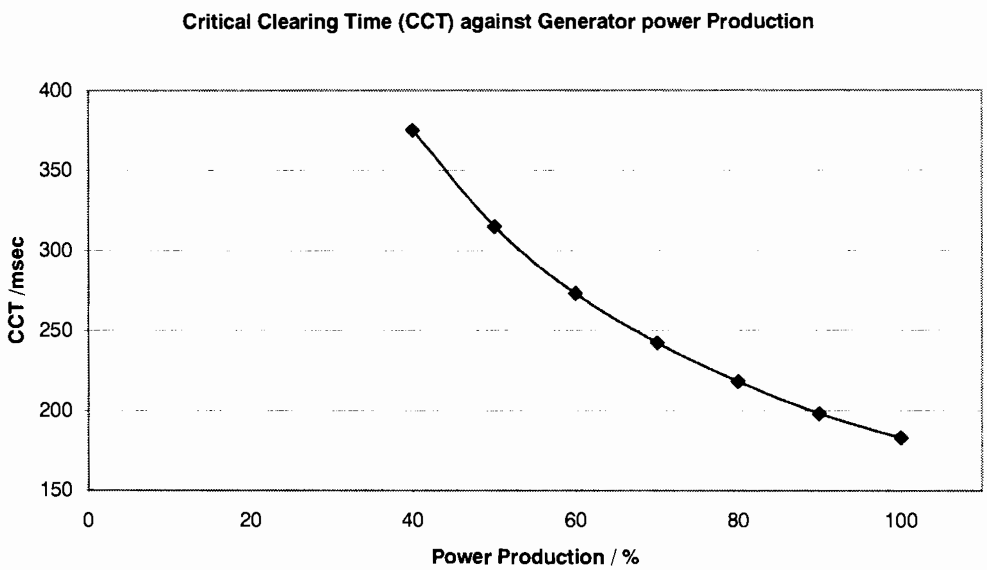


Figure 5.14: Effect of generator loading on the critical fault clearing time

Figure 5.14 shows that the loading of the generator greatly affects the stability of a machine. The more heavily loaded a machine becomes the smaller the critical clearing time becomes, and the more lightly loaded a machine becomes the larger the CCT becomes. For 60% increase in power production the CCT dropped by 50%, which is very high.

5.3.7 ANALYSIS OF RESULTS

The results show that for an increase in synchronous reactance (Xd), transient reactance (X'd) and sub-transient reactance (X"d) the critical fault clearing time (CCT) will be lowered. From these three parameters it was found that the transient reactance (X'd) had the highest effect on the CCT, followed closely by sub-transient reactance, and the synchronous reactance had the least effect on the critical fault clearing time (CCT). It would therefore be ideal to have synchronous generators that are connected to the distribution network which have been designed to have small values of Xd, X'd and X"d, in order to increase the transient stability of the distribution network to which they are connected.

As expected the results of this case study also revealed that an increase in inertia constant (H) results in an increase in the critical fault clearing time (CCT). From all the generator parameters that were investigated it was realised that the Inertia constant (H) has the highest effect on the CCT value of the generator. Most small generators have small inertia values, and this leads to the generators having small CCT values which reduces the transient stability of distribution networks.

Generator loading had a great impact on the transient stability of the generator. This result was expected because when a generator is lightly loaded it has a large reserve margin that can be used to assist the generator to recover from any large disturbances it is subjected to.

The results of this case study show that generators that have low transient reactance values as well as high inertia values would have high critical fault clearing times. It would be beneficial for the distribution network to be connected with these types of generators so that the generators do not degrade the transient stability of the network. If these types of generators were to be designed they would have a shorter length (than that of a similar rated generator) in order to reduce the transient reactance as low as possible, and they would have a larger diameter (than that of a similar rated generator) in order to have a high inertia constant. This type of generator would have a higher than normal manufacturing cost due to the unique design.

5.4 SUMMARY OF TRANSIENT STABILITY STUDIES

In this chapter transient stability studies were conducted on two different case studies. The first case study was conducted on a non-actual system that does not exist, and was connected with wind and hydro DG. The second case study was conducted on an existing Mbabane distribution network that is connected with a hydro generator. The objective of both case studies was to investigate the conditions that lead to transient instability. It was evident that the occurrence of transient disturbances close to distributed generators easily led to the destabilisation of the synchronous generator.

The aim of the first case study was to investigate how the fault location and the load condition on a distribution network affects the critical fault clearing time. The results of the first case study showed that the closer a large disturbance is to a synchronous generator the shorter the critical fault clearing time, and the further away a large disturbance is from a synchronous generator the longer the critical fault clearing time. This result is important because it can assist with the settings of protection times, and it is evident that the protection operating times closer to the generator have to be faster than the CCT of the DG in order to prevent the synchronous generator from losing stability. The first case study results also showed that when the load that is being supplied by a DG increases the CCT decreases linearly.

The aim of the second case study was to investigate how different parameters of a synchronous generator impact the transient stability of the distribution network it is connected to. The results of this case study showed that for an increase in synchronous reactance (Xd), transient reactance (X'd), and sub transient reactance (X"d) the CCT was lowered. Transient reactance (X'd) was found to have the highest effect on CCT. An increase in Inertia constant (H) resulted in a significant increase in CCT. It would therefore be ideal to have generators that have high inertia constants and low Xd, X'd, X"d, however this would result in the generators being more expensive. This is because specially designed generators with shorter lengths (to reduce the transient reactance) and larger diameters (to increase the inertia constant) have to be designed.

CHAPTER 6

VOLTAGE STABILITY SIMULATIONS AND ANALYSIS

This chapter presents voltage stability studies that were carried out in this thesis. These stability studies were carried out on model non-actual systems that were chosen to investigate key voltage stability issues that are raised by the connection of DG units on a distribution network. This chapter utilises two types of distributed generation technologies in the stability studies, these include wind generators as well as hydro generators. The technologies represent different conventional electrical machines. Two case studies were conducted in order to investigate various cases of stability in order to identify limiting factors where DG is connected to weak distribution systems typical of Africa. The case studies that were conducted include;

- A 'typical' small network with wind DG connected to a 11kV grid,
- A electrically weak network with wind and hydro DG connected to a 11kV grid

The typical small network with wind DG connected is the same type of network that was used in chapter 5, except it now only has the wind DG connected to it. As mentioned in the previous chapter, it was designed to represent a typical distribution network that would exist in Southern Africa in order to highlight voltage stability issues that are raised when DG is connected to a distribution network.

The electrically weak distribution network was specifically selected to highlight voltage instability on a weak network. The literature survey revealed that voltage stability can be a problem on weak networks, and can be a bigger problem if induction generators are connected to the weak network, and weak networks are common in rural electricity networks in Africa. Hence case study 4 investigates voltage stability on a weak network.

This chapter contains four sections. The first section introduces voltage stability analysis of generators that are connected to the network. The second section is the third case study of the thesis that investigates the critical stability limit of wind generators that utilise induction generators and the effect these generators have on the voltage stability of a distribution network. The third section is the fourth case study of the thesis and it investigates voltage stability on a weak network connected with DG. Lastly a summary of the chapter is presented.

6.1 VOLTAGE STABILITY ANALYSIS

Voltage stability is concerned with the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. The objective of voltage stability studies is to determine whether the network is able to maintain steady acceptable voltages under all conditions. Voltage stability can be analysed using the static analysis method or the dynamic analysis method. As mentioned in section 4.1.3, this thesis focuses on large disturbance voltage stability and this type of stability is best analysed using the dynamic analysis method. The dynamic analysis method is useful for detailed study of specific voltage instability situations. Voltage stability was determined using time domain simulations of the system. [31]

The main factor causing voltage instability is the inability of a power system to maintain a proper balance of reactive power in a system. As mentioned in the literature survey, a distribution network that has induction generators connected and a high percentage of reactive power loads like induction motors, there is an increased possibility that the network can easily go into a state of voltage instability. In addition, the reactive power demand of induction generators increases during large disturbances that result in the generators over speeding. For this study, induction generators were used as generators for wind turbines.

The different aspects of this chapter that will be looked into include;

- Critical stability limit of induction generators
- Impact of power production on the critical stability limit of an induction generator
- Voltage stability impact of induction generator on the network to which it is connected
- Voltage stability on a weak distribution network

6.2 CASE STUDY 3 – Typical Small Network With Wind DG Connected To A 11kV Grid

The system in this case study is similar to the system that is used in case study 1, but this system does not have a synchronous generator connected. The literature survey revealed that when distributed generators that utilise induction generators are connected to a distribution network there is an increased probability that the network could have voltage stability problems. This is caused by the fact that induction generators draw large amounts of reactive power when they are subjected to large disturbances. And since the main factor causing voltage instability is the inability of a system to maintain a proper balance of reactive power in the system, there is no need to include synchronous machines that have independent control of reactive power. The same type of network used in case study 1 was utilised for this case study because it is the typical network that is found in rural areas in Southern Africa that is often the attractive area for wind energy development.

This case study firstly seeks to investigate how the asynchronous generators react after a fault condition on the network, and how this affects the voltage stability of the distribution network it is connected to. Secondly this case study seeks to investigate the impact of power production on the critical stability limit of induction generators. It lastly seeks to investigate the voltage stability impact of connecting induction generators on distribution networks.

6.2.1 NETWORK DESCRIPTION

The distribution network consists of 6 bus bars, 2 transformers, 9 lines and 3 voltage levels. This network does not exist but was designed to highlight stability issues that raised when DG is connected to a distribution network. The network represents a radial distribution network that is mainly found in rural areas in Southern Africa. The loads are connected to the 11kV feeders, and the grid supply point is at the 132KV bus bar. The line conductor that was used for all the distribution lines is a 63mm ACSR (Aluminium Conductor Steel Reinforced).

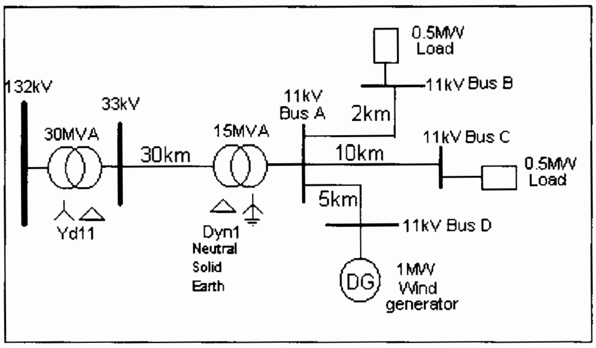


Figure 6.1: Case study 3 distribution network diagram

6.2.2 GENERATORS

A 1MW induction wind generator was the only distributed generator used in this case study. The generator data for this machine is listed in the Appendix D. This generator does not have any controls, and consists of the induction generator generating on its own. A constant mechanical torque was applied to the rotor of the induction generator, in order to simplify the investigation.

6.2.3 DISTURBANCE

A three-phase fault was inflicted on the 11kV bus bar A throughout the investigation. The transient disturbance was inflicted on this bus bar, because this is a central bus therefore it would affect all the loads as well as the induction generator. A three-phase fault is one of the most severe disturbances that can occur on a distribution network, and it threatens the voltage stability of the network.

6.2.4 LOAD MODEL

The load model that was used was a mixture of static and dynamic loads, but mainly dynamic loads. The load model mainly represents industrial loads. Sub-section 4.3.3 covered the theory on the load model that was used in the simulations.

The loads modelled included two balanced 0.5MW loads, with power factors of 0.85. Eighty percent of the load was modelled as a dynamic load and twenty percent of the load model was modelled as a static load. The load model mainly has a dynamic component because dynamic loads vary considerably and rapidly to changes in voltage and frequency. Therefore when a transient disturbance is introduced onto the network voltage instability would be introduced onto the network.

6.2.5 LOAD FLOW STUDY

A load flow diagram of case study 3 is shown in Appendix D. The load flow results of the case study 3 network show that a significant amount of reactive power is imported from the external grid. The wind generator is able to supply the network with the required active power. Under steady state conditions the wind generator draws the largest proportion of reactive power. The voltage levels on the bus bars are all within 10% of the nominal voltage, with the voltage at the wind gen bus being exactly 10% below nominal voltage. The load flow results indicate that under normal conditions the network is stable

6.2.6 SIMULATION

When carrying out the stability studies the critical stability limit of the wind generator was established, this was after a three phase fault had been introduced on the 11kV bus bar A. The critical stability limit of the wind generator was established in order to know the fault duration that would result in the wind generator losing its stability. The critical stability limit of the induction generator hence corresponded to the maximum fault duration before the induction generator lost its stability. The corresponding maximum speed of the induction generator was also recorded. Once the critical stability limit of the wind generator had been established, the focus was now on the voltage stability of the distribution network when the wind generator had just lost its stability. Since the main factor causing voltage stability is the inability of the power system to main a proper balance of reactive power in the system, the active and reactive power of the wind generator was monitored before and after the transient disturbance. The voltage profiles of the bus bars were also monitored. These simulations were performed at different wind generator power production settings in order to gain a better understanding of the concept.

RESULTS OF IMPACT OF INDUCTION GENERATOR ON THE VOLTAGE STABILITY OF A DISTRIBUTION NETWORK

Power production /MW	% Power production	Max fault duration before losing stability /msec	Corresponding Max Speed /p.u.
0.5	50%	2973	1.580
0.6	60%	1755	1.438
0.7	70%	1150	1.351
0.8	80%	804	1.293
0.9	90%	588	1.250
1.0	100%	442	1.217

Table 6.1: Results for critical stability limit and critical stability speed of an induction generator

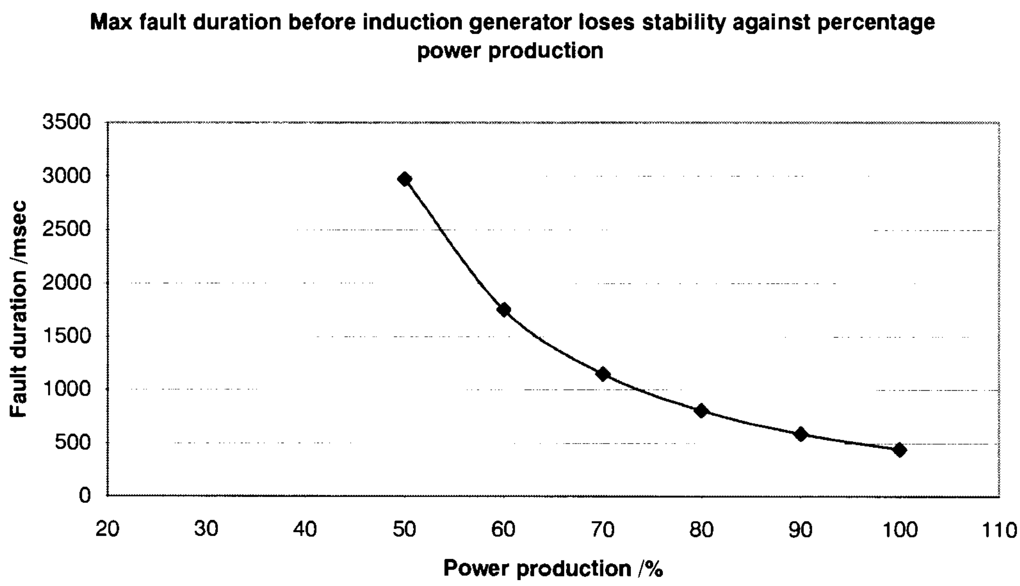


Figure 6.2: Effect of power production on the critical stability limit of an induction generator

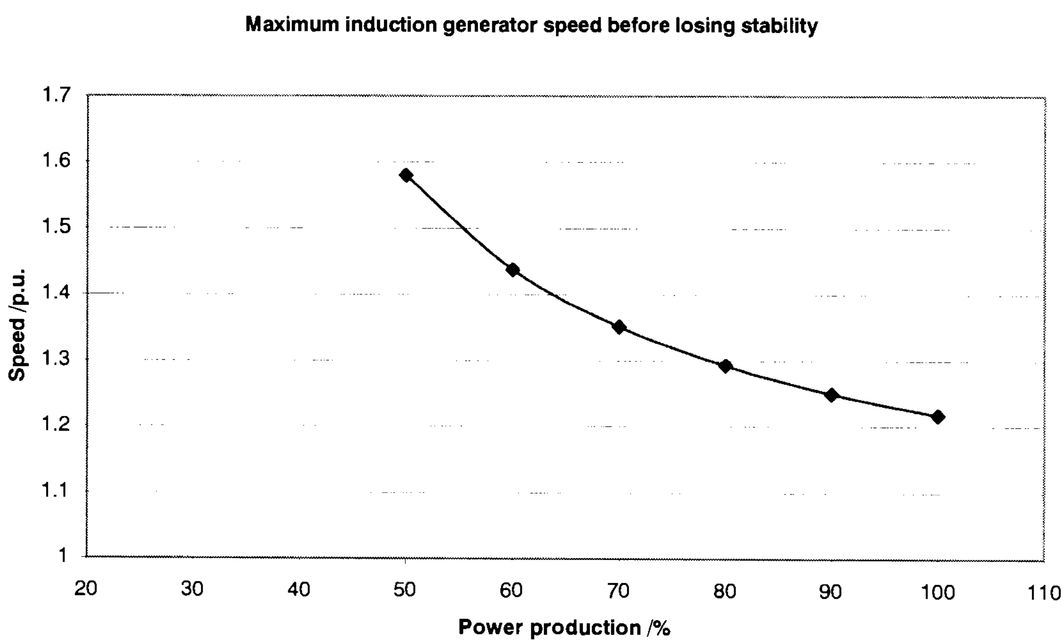


Figure 6.3: Effect of induction generator power production on the critical stability speed

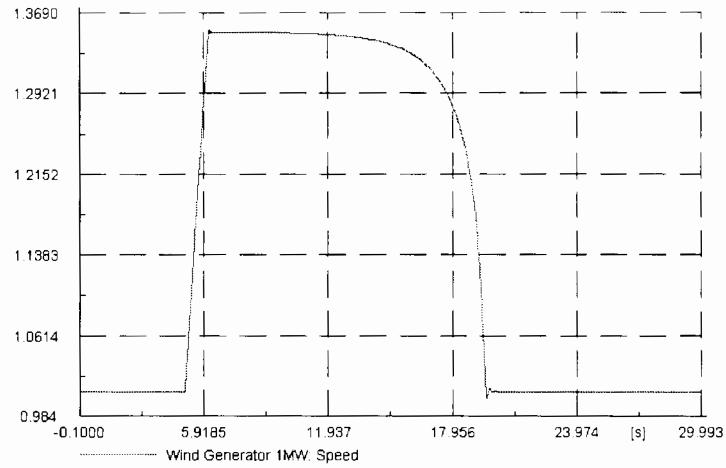


Figure 6.4: Induction generator speed for fault duration of 1150msec and power production of 70%

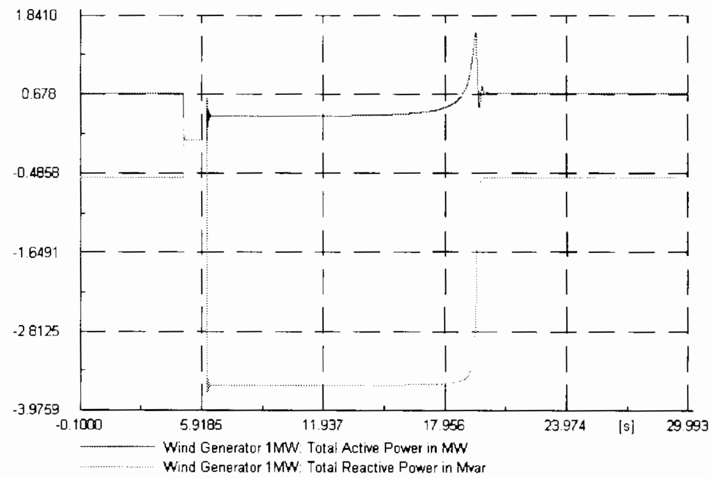


Figure 6.5: Active and reactive power of induction generator after a fault duration of 1150msec and power production of 70%

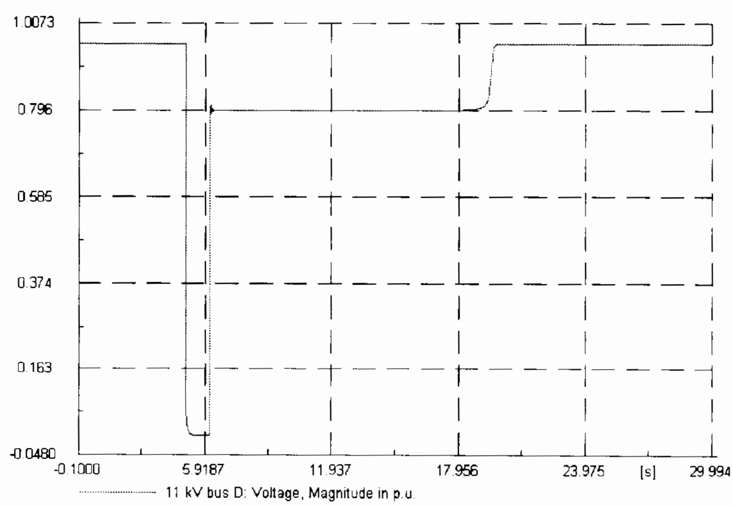


Figure 6.6: Voltage profile at 11kV bus bar D after fault duration of 1150msec and power production of 70%

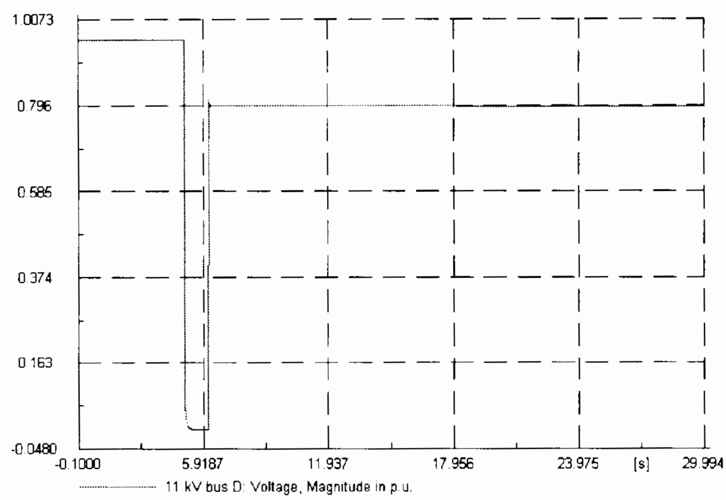


Figure 6.7: Voltage profile at 11kV bus bar D after fault duration of 1151msec and power production of 70%

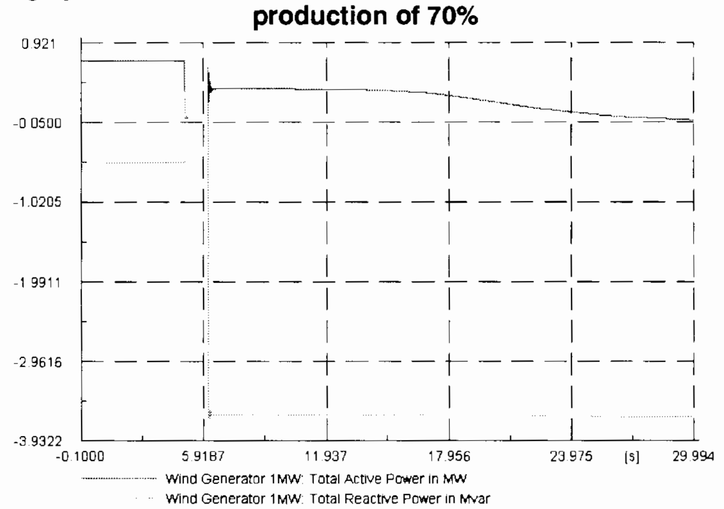


Figure 6.8: Active and reactive power of the induction generator after a fault duration of 1151msec and power production of 70%

The results of Table 6.1, Figure 6.2 and Figure 6.3 clearly indicate that when the power production of an induction generator increases the generator quickly reaches its stability limit. This is because when the power production of the generator increases the generator starts operating close to its rated values. When considering the maximum fault duration, Figure 6.2 shows that there is exponential relationship between maximum fault duration and the percentage power production. When the induction generator is lightly loaded it can handle longer duration faults, whereas when the generator is heavily loaded it can handle shorter duration faults. This result was expected after covering the induction generator stability limit in chapter 4. Similarly Figure 6.3 illustrates that, when the induction generator is lightly loaded it can afford to rotate at higher speeds before reaching its stability limit, whereas when the induction generator is heavily loaded it can only afford to over speed by a small margin before it reaches its stability limit. The reason why the generator over speeds is caused by the fact that during the fault the generator output power drops to zero but the prime mover is still supplying the input mechanical power, the prime mover therefore accelerates the rotor and causes it to over speed. Figure 6.4 illustrates the speed profile for maximum fault duration of 1150msec at a power production of 70% that just avoids the induction from going into a state of instability (going over the critical stability limit). When the fault is cleared, if the generator has not gone over its critical stability limit, the generator stops accelerating and decelerates down to its rated speed. However while it is decelerating it draws large amounts of reactive power (As shown in Figure 6.5) that depresses the voltage on the 11kV bus bars, as shown in Figure 6.6. However because the generator is able to recover the voltage at the 11kV bus B returns to its nominal value. Figure 6.6 is interesting because it shows that it takes approximately 12 seconds for the induction generator to recover, which is quite a long time.

When the induction generator over speeds and goes over the stability limit, the voltage profile of local bus bars is affected, as shown in Figure 6.7. It is clear from this voltage profile that after the voltage depression the voltage drops and does not return to its nominal value because the induction generator is still drawing large amounts of reactive power (as shown in figure 6.8) because it is in a state of voltage instability. The implication of this is that the voltage profile of the other feeders that are connected to the 11kV bus A will also drop. The induction generator that is in a state of instability therefore has to be disconnected from the network, because of the large amounts of reactive power that it is drawing. Wind turbines generally trip when they reach a speed of 10% above the synchronous speed to avoid damaging the prime mover. If the loads connected to the distribution network have a high penetration of induction motors and a long duration fault occurred, this would mean that large proportions of reactive power would be drawn from the system, including the amount of reactive power that would be drawn by the induction generator, and the system would definitely go into a state of voltage instability. The simulation graphs illustrating how different parameters responded just before and after the induction generator went over the critical stability limit are shown in Appendix D for different power production percentages.

When an extra induction generator was added to 11kV bus bar D, the maximum fault duration before both generators reached their critical stability limit at a power production of 100% was reduced to 251msec from 442msec. The reactive power demand of the generators increases when they have exceeded their critical stability limit because the number of generators has been doubled, which therefore means the voltage is depressed even further. This effect is illustrated in Figure 6.9. When the number of induction generators connected in parallel is increased and the generators lose their stability and they start over speeding, the voltage profile on the 11kv bus bars is further depressed.

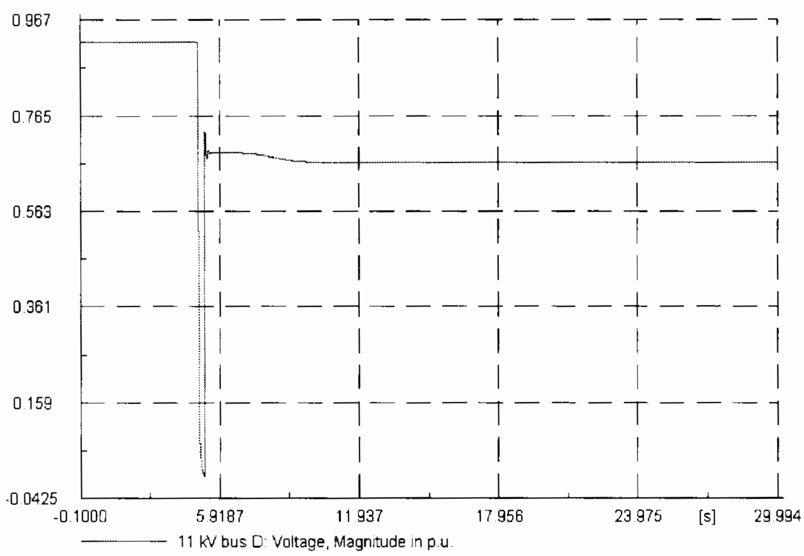


Figure 6.9: Voltage profile at 11kV bus bar D after fault duration of 252msec and power production of 70% with 2 generators connected

6.2.7 ANALYSIS OF RESULTS

This case study has shown that induction generators contribute significantly to voltage instability, mainly because after the occurrence of a large perturbation the reactive power demand of the induction generators is high. When a high penetration of induction generators is allowed onto a system the local network voltage profile can be suppressed significantly after the occurrence of a long duration severe disturbance because the reactive power demand would be even increased. Just like synchronous generators, induction generators showed that when the power production was increased the generator quickly reached its stability limit. If the induction generator used in this case study was a synchronous machine the voltage profile on the network would fluctuate between two set points due to the loss of synchronism with the network.

6.3 CASE STUDY 4 – Electrically Weak Network With Wind and Hydro DG Connected To A 11kV Grid

The radial distribution network that is used in this case study was designed to highlight key voltage instability issues that are raised by the connection of DG units on a weak distribution network. This network has two generators that are connected at the end of the radial distribution network, and the total power capacity of these generators adds up to 2.7MW. The total load connected onto this distribution network is 3MVA and is also connected at the end of the radial distribution network. The radial distribution network is connected with a grid supply point at 66kV, however the fault level at the grid supply point is low in accordance with the weak distribution network. Since the focus of this case study is to highlight key voltage stability issues that are raised on a weak distribution network, when carrying out stability studies the reactive power demand by network components was increased. This was done in order to create a condition on the network that would easily lead to voltage instability.

6.3.1 NETWORK DESCRIPTION

The distribution network consists of 8 bus bars, 1 transformer, 6 lines and 2 voltage levels. The network was designed to emulate typical weak radial distribution networks that are abundantly found in the Southern African region. The distribution network has a supply point that is connected at a voltage level of 66kV. The loads as well as the generators are connected at a voltage level of 11kV. The line conductor that was used for the distribution lines is a 63mm ACSR (Aluminium Conductor Steel reinforced) cable. The lengths of the lines were arbitrarily chosen to vary the impedance of the lines. Figure 6.10 illustrates the network that was designed for this case study.

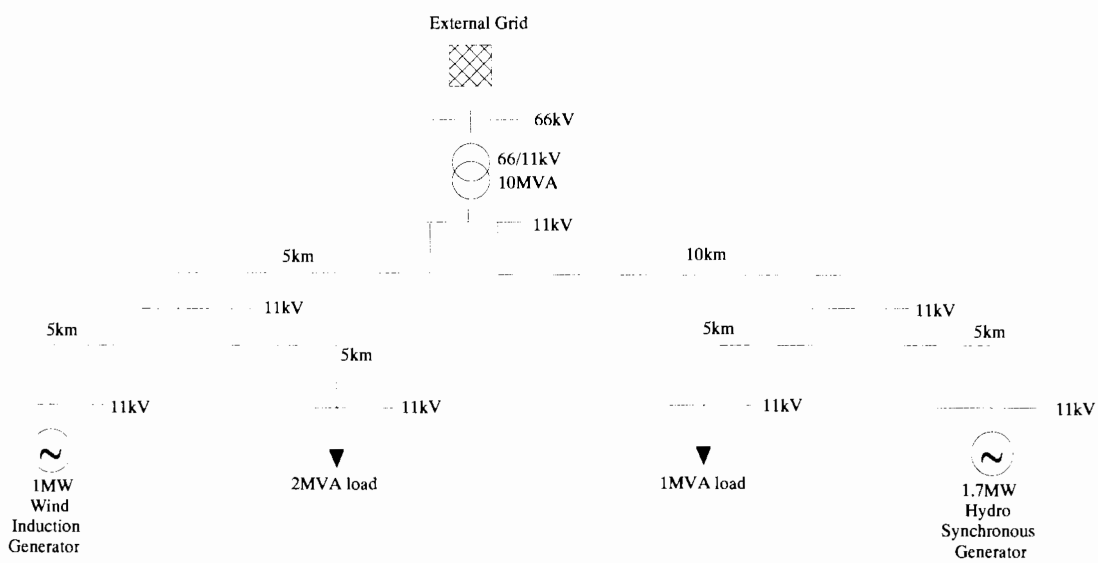


Figure 6.10: Single line diagram of a weak radial distribution network

6.3.2 GENERATORS

A 1.7MW synchronous hydro generator as well as a 1MW asynchronous wind generator were the generators that were used in this case study. The generator data for these machines is listed in

Appendix E. The hydro generator has a governor as well as an exciter connected to it, and the parameters of these controllers are also available in the appendix.

6.3.3 LOAD MODEL

The type of load model that was used in this case study was a mixture of static and dynamic loads. This type of load model tried to represent mainly industrial loads that utilise a lot of induction motors. Sub-section 4.3.3 covered the theory on the load model that was used in the simulations.

The types of loads modelled include a balanced 1MVA and 2MVA load, with power factors of 0.85. Eighty percent of the load model was dynamic and twenty percent was static. This type of load model therefore had a higher percentage of dynamic loads, because it mainly represented industrial loads.

6.3.4 DISTURBANCE

In order to create a voltage unstable network a large disturbance was introduced onto the network. The large disturbance introduced was a three-phase fault because it is one of the most severe faults that can occur on a distribution network. The three-phase fault was inflicted at the generator terminals of the induction generator in order to increase the reactive power demand of the induction generator.

6.3.5 LOAD FLOW STUDY

A load flow diagram of Case study 4 is shown in Appendix E. The load flow results of the case study 4 network show that a 1.96Mvar of reactive power is imported from the external grid, even though the hydro generator injected 0.51Mvar of reactive power. The loads, wind generator and distribution lines were the components that demanded reactive power. The active power provided by the wind generator and the hydro generator almost met the amount required by the network. The voltage levels on all the bus bars are within 10% of the nominal voltage. The load flow results indicate that under normal conditions the network is stable.

6.3.6 SIMULATION

A scenario where there was a high demand for reactive power but not enough to supply it was created. This is because one of the main factors causing voltage instability is the inability of the power system to maintain a proper balance of reactive power throughout the system. The type voltage stability that was investigated in this case study was large disturbance voltage stability. This type of voltage stability was selected because it is the most severe and the most likely type that would occur on a typical weak Southern African distribution network. In order to ensure that the network was a weak radial distribution network the external grid was made to have a low fault level with a high impedance.

Firstly a load flow of the designed network was carried out to make sure that voltage levels, loadings and power flows were within limits. A large disturbance in the form of a three-phase fault was then introduced onto the terminals of the induction generator. The duration of the disturbance was longer than the critical stability limit of the induction generator in order to increase the reactive demand of the induction generator. While the network was trying to recover from the large disturbance the synchronous generator was disconnected from the system since it is one of the sources of reactive power. The voltage profiles at the different bu s bars were then monitored.

A two second duration fault was introduced onto the network at the terminals of the induction generator. This fault resulted in the induction generator going over its stability limit, which was found to be 0.136 seconds. Figure 6.11 shows the wind generator speed constantly increasing and not being able to recover. Due to the weakness of the radial network the two second fault also resulted in the synchronous generator also losing its stability. Figure 6.12 shows the rotor angle of the hydro generator after the 2 second three phase fault at the terminals of the induction generator. However 2 seconds after the fault is cleared, the hydro generator is removed from the system. The simulation time is extended to 40 seconds for evaluating the system performance due to the events.

RESULTS OF VOLTAGE STABILITY IMPACT OF DG ON A WEAK DISTRIBUTION NETWORK

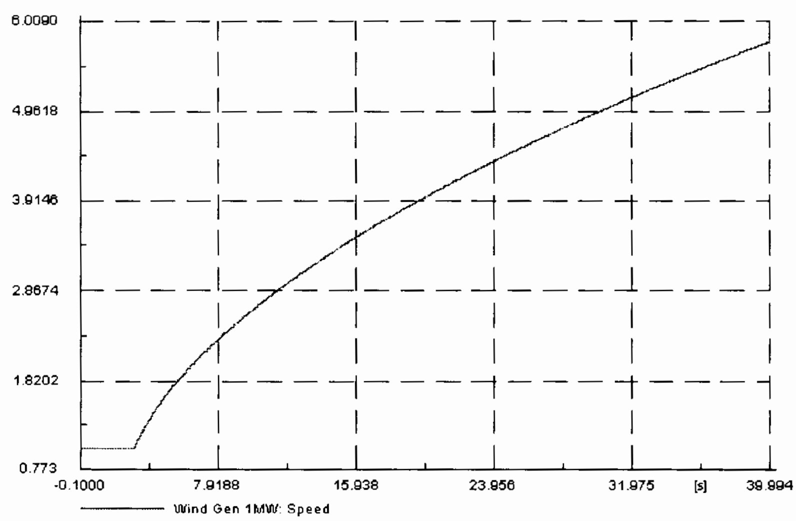


Figure 6.11: Wind speed generator speed after a three phase fault dt = 2secs at the terminals of the generator

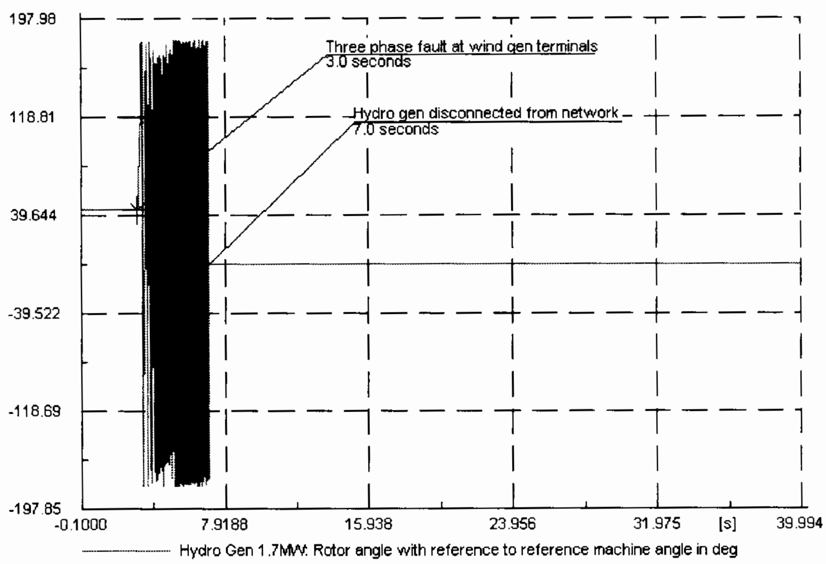


Figure 6.12: Hydro generator rotor angle after a three phase fault dt = 2secs at 3secs, and hydro gen disconnection from network at 7 secs

During the three-phase fault on the terminals of the hydro generator both the active power and reactive power of the induction generator were forced to zero mega watts. When the fault was cleared the reactive power demand by the induction generator rapidly jumped up and down between –1.1MW and –0.15MW until the hydro generator was disconnected. When the hydro generator was disconnected the reactive power gradually settled at –0.43MW. The active and reactive power responses of the induction generator are shown in Figure 6.13.

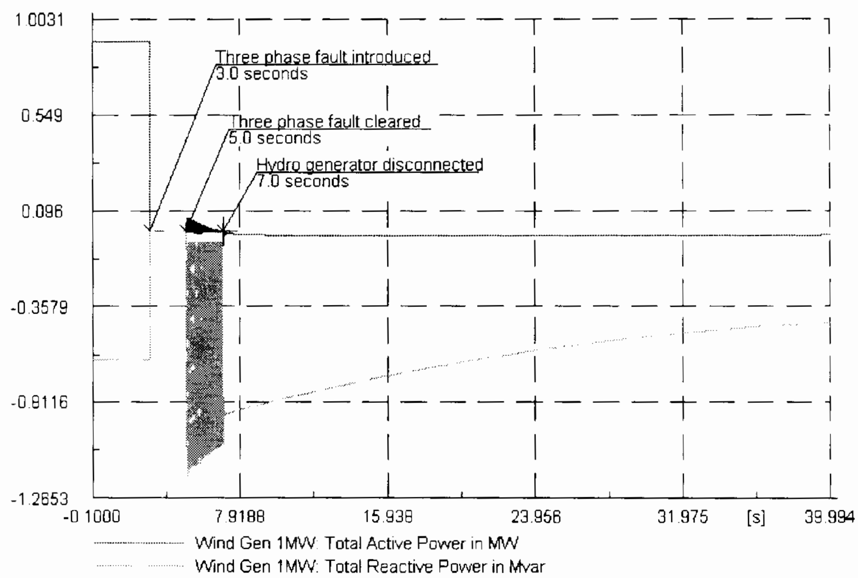


Figure 6.13: Active and reactive power of wind generator

When the hydro generator is disconnected from the network the voltage profile at the bus bars is observed to progressively fall. This is a definitely a sign of voltage instability on the distribution network, as covered in chapter 4. The voltage profiles at the different bus bars are shown in Figure 6.14, 6.15 and 6.16.

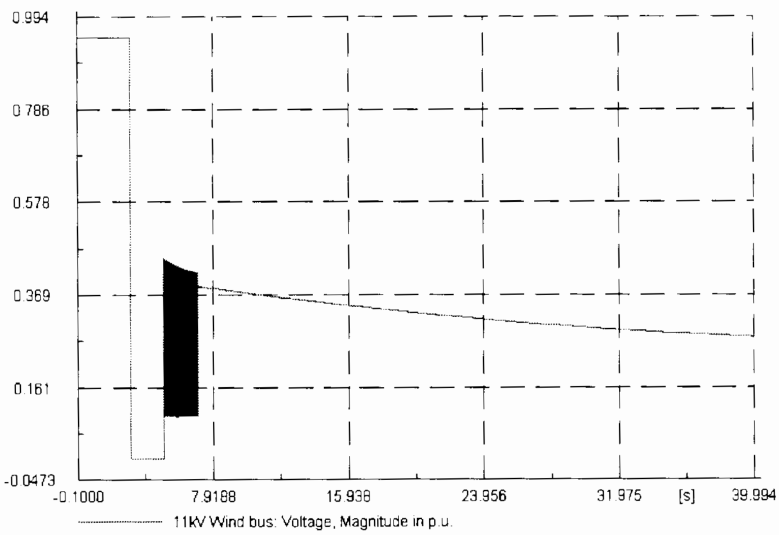


Figure 6.14: Voltage profile at 11kV wind bus

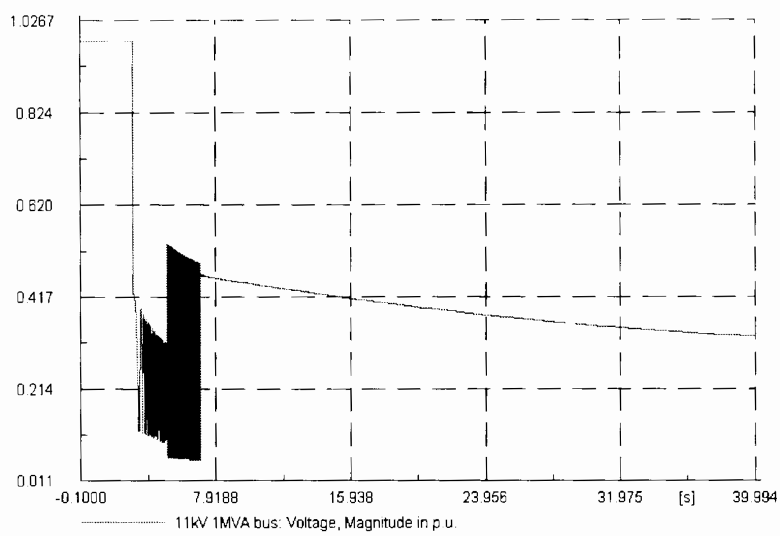


Figure 6.15: Voltage profile of 11kV 1MVA load bus

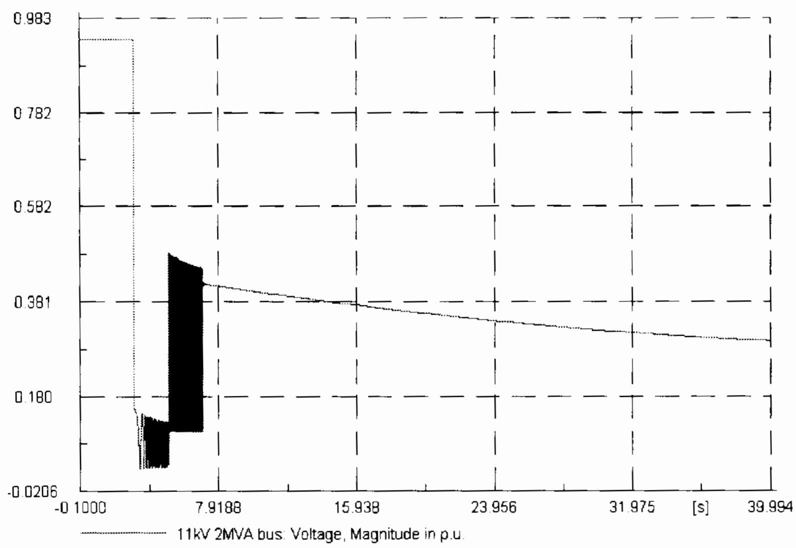


Figure 6.16: Voltage profile of 11kV 2MVA load bus

EFFECTS OF ELECTRICALLY WEAK NETWORKS

The network in this case study was purposefully set up as an electrically weak network. This was done by ensuring a low fault level at the external grid connection point, and also a high impedance at the external grid connection point. The impedance of the 11kV distribution lines was also made high by increasing the lengths of the 11KV distribution lines.

The effects of the electrically weak network were clearly visible on voltage profiles of the network bus bars during the simulation. The weak distribution network suffered extreme voltage fluctuations, especially after the transient disturbance was introduced. These voltage fluctuations are evident on Figure 6.14-6.16. These fluctuations were accentuated on the bus bars that were connected with a load. The effects of the electrically weak network resulted in the voltage stability problem, caused by the high reactive power demand of the induction generators, becoming worse. This type of network quickly went into a voltage unstable state when the transient disturbances occurred.

6.3.7 ANALYSIS OF RESULTS

From the above results it can be concluded that when a large disturbance occurs on a weak radial distribution network that is connected with DG that utilises an induction generator, the voltage stability of that network can be greatly affected. When a large disturbance occurs on a weak distribution network the effect of the disturbance is greatly felt throughout the distribution network. In this case study, after the occurrence of the disturbance the voltage profiles of all the bus bars dipped to low values, even the voltage profiles of laterally connected feeders. This was caused by the electrically weak networks.

It is evident that with a high penetration of reactive power demanding components, the voltage stability of that particular network can be worsened and the possibility of the distribution network going into a state of voltage instability is increased. The network components that demanded higher quantities of reactive power include induction generators and dynamic loads. The results of this case study showed that in a scenario where there is an imbalance of reactive power on a distribution network that network is likely to be voltage unstable. This therefore resulted in the voltages of the bus bars progressively decreasing. It was also evident that the effects of electrically weak distribution networks can accentuate voltage instability.

6.4 SUMMARY OF VOLTAGE STABILITY STUDIES

In this chapter voltage stability studies of distribution networks that are connected with DG were conducted. The stability studies were separated into two case studies. Case study 3 was conducted on a 'typical' small network with wind DG connected to a 11kV grid, extending the model used to study transient stability in chapter 5. Case study 4 was conducted on an electrically weaker 11kV network, also with wind and hydro DG connected.

The aim of Case study 3 was to investigate how the induction generators react after a fault condition on the network, and how this affects the voltage stability of the distribution network it is connected to. The results from Case study 3 indicated that the generator quickly reaches its stability limit when the power production of an induction generator increases. This case study also demonstrated the impact of unstable induction generators on a distribution network. The large amounts of reactive power that are drawn by the induction generator when it is unstable were identified to cause voltage instability on the distribution network. When the number of induction generators connected to a distribution network was increased and the generators lost their stability, the voltage dropped even further, increasing the likelihood of voltage collapse. This case study showed that induction generators significantly contribute to voltage instability.

The aim of Case study 4 was to investigate voltage stability on a weaker distribution network that is connected with distributed generation. The results of this case study revealed that voltage instability could easily occur on a weak distribution networks that are connected with induction generators, this would be after the occurrence of a severe disturbance on the distribution network.

CHAPTER 7

STABILITY STUDY OF THE TRANSKEI DISTRIBUTION NETWORK

This chapter presents a stability study of the Transkei network with distributed generation. Transkei is a former homeland located in the Eastern Cape of South Africa. The Transkei distribution network has four hydro power plants with a total of ten hydro generators connected. These generators came into existence as far back as 1979 and the most recent was commissioned in 1983. This stability study was separated from the case studies that were conducted in chapter 5 and chapter 6 in order to have a detailed study of an existing DG example from the Southern African region, that would also include a historical overview of the system. In order to increase the credibility of this study a visit to the region was undertaken by the author to gather information that would aid the investigation and to get practical experience of how the system operates.

This chapter explains why the Transkei system is an example of DG, especially in relation to the DG definition that was presented in Chapter 2. The chapter presents and conducts a transient stability study of the Transkei distribution network, and investigates the impact caused by the governor on the transient stability of the hydro generator. Furthermore the chapter examines the methods that have been used by the utility to improve the stability of the Transkei network.

The chapter is divided into 4 sections. The first section reviews the DG status of the Transkei network, and analyses the process by which the hydro plants generate power. The next section assesses the Transkei distribution network and presents its network components, as well as future plans of the Transkei network. The third section presents transient stability studies that were conducted on the Transkei network. And lastly the fourth section summarises this chapter.

7.1 REVIEW OF DG EXISTING IN TRANSKEI

Distributed generation in Transkei consists of only hydro generation plants. The hydro generation plants include Mbashe, Ncora, Umtata 1st falls and Umtata 2nd falls. Table 7.1 lists the power ratings of the generators as well as the number of generators of the hydro power plants.

Hydro station	Number of hydro generators	Power ratings / MW
Ncora	3	1.6, 0.4, 0.4
Mbashe	3	14, 14, 14
First falls	2	3, 3
Second falls	2	5.5, 5.5

Table 7.1: Power ratings of hydro generators connected to the Transkei Network

7.1.1 VERIFICATION WHETHER HYDRO PLANTS IN TRANSKEI ARE DG

As mentioned above, Transkei has four hydro power plants. It is important to verify that these generators are indeed distributed generators and that they fall within the boundaries of the definition presented in chapter 2.

The hydro generators that exist in the Transkei are distributed generators because of the following reasons;

- They are a source of electric power
- They are interconnected with an electricity supply at voltages of less than 132kV
- They are not centrally dispatched by National Control Centre in Germiston, but by a provincial control centre in East London
- They are not trading participants in a power pool
- They are within the range of small, medium and large generators (Table 2.1)

7.1.2 WATER SUPPLYING HYDRO POWER PLANTS

Two river systems supply the four hydro power plants located in the Transkei. The river systems have dams that store the water. The dam levels are monitored with electrical meters, and are recorded by the power station controllers every hour. The dam levels are monitored because each dam has a minimum operating level, and to curb water wastage that may result if the dam overflows. Water may be spilt over the balancing dam wall due to excessive rain or an outage of a generator. The dam level measurement equipment has been set up to be able to measure the dam level beyond the spill over level. This makes it possible to calculate the total amount of water spilt over a period of time. The amount in Rands of lost revenue can then be calculated.

The Umtata River System

The Umtata river system first supplies the Umtata 1^{st} falls hydro station and then supplies the 2^{nd} falls hydro station. The water is stored at Umtata Dam and is released into the Umtata river when generation is required. It takes the water 8 hours to flow from Umtata dam to 1^{st} falls. Therefore no power can be suddenly generated if the gates at Umtata dam are closed. The water head of the 1^{st} falls power station is 27m. The power station is located very close to the 1^{st} falls dam. The 1^{st} falls hydro station has an electrical generation capacity of 6 MW from two 3 MW generators.

Once the water from the 1^{st} falls hydro station is discharged back into the Umtata river, it takes 8 hours to flow before it reaches the 2^{nd} falls dam. The water head of the 2^{nd} falls power station is 45m. The power station is also located very close to the 2^{nd} falls dam. The 2^{nd} falls hydro station has an electrical generating capacity of 11 MW from two 5.5 MW generators. Both these dams were constructed on natural waterfalls.

The Mbashe River System

The Mbashe river system first supplies the Ncora hydro station. The Ncora station has an electrical generating capacity of 2,4 MW from one 1.6 MW generator and two 0.4 MW generators. The water discharged from the Ncora power station flows into the Mbashe river. The Mbashe river then feeds the Mbashe dam which is constructed at a place called Collywobbles. The Mbashe dam has silt problems, and it hence has a dredger that reduces the silt that accumulates near the dam wall. The dam is located approximately 20km away from the hydro station. The water is channelled from the dam to the station through a tunnel with a diameter of approximately 6 metres, and the tunnel length is approximately 4.5km. The approximate head of the power station is 120m. Mbashe hydro station has an electrical generating capacity of 42 MW from three 14 MW generators. The water that is discharged from the Mbashe hydro station is discharged back into the Mbashe river and flows into the sea.

Figure 7.1: Mbashe Dam

Figure 7.2: Mbashe Dam Wall

7.1.3 GENERATING SCHEDULE OF THE TRANSKEI HYDRO POWER PLANTS

Generation at the Transkei hydro power stations depends on the water availability, therefore careful monitoring and control of water is important. Normally during the rainy season the generators operate 24 hours or close to 24 hours to prevent water from spilling over the dam wall. The rainy season approximately starts in November and ends in March. Sometimes the weather is unpredictable and it rains in April or even in May. During the dry season the generation mainly occurs during peak hours. The hydro generators are hence peak lopping plants during the dry season. The East London control centre usually instruct the hydro station operators to synchronise the hydro generators one hour before the peak period, and instructs them to disconnect the hydro plants one hour after the peak period. The peak period is defined by the system performance, and not by the Eskom Time of Use (TOU) tariffs.

Maintenance is done during the low rain season. This is because the water supply during this season is low, and the non-operation of a hydro generator does not affect the generation schedule because water is limited. No maintenance occurs during the rainy season in order to avoid water wastage.

7.1.4 TRANSKEI HYDRO POWER STATIONS

Mbashe Hydro Power Plant

Mbashe hydro power plant has an electrical generating capacity of 42MW with three 14MW synchronous generators. The type of hydro turbine used by the plant is a Francis turbine that utilises a horizontal axis generator. The main components of this hydro power plant include the main inlet valve (MIV), turbine, flywheel, generator and governor, as shown in Figure 7.3 below.

Figure 7.3: Mbashe hydro power station

Stability related points about Mbashe power station that were picked up while visiting the station are as follows;

- The generators operate in automatic mode, therefore once the generators are synchronised onto the network the automatic control takes over. A null balance meter is used for a smooth change over from the manual to auto voltage control. With the exciter field control switch in the auto position the AVR controls the voltage automatically.
- Synchronising of the hydro generators at the station is manually done by the station operators using a synchroscope. No automatic synchronising facility is available. The manual synchronising of the generator takes approximately 3-5 minutes, but could take longer. The station operators utilise the station transformer taps to assist them with synchronising by controlling the system voltage level of the bus bars to which the generators are to be connected.
- The generators use a brushless excitation system, however the response of the AVR has been realised to be slow. This results in the generator hunting after some disturbances on the system. A new and faster AVR was installed in July 2002, after the visit. As mentioned in section 3.1.1, using a high response excitation system maintains the power transfer capability of the generator even if the network voltage is depressed by a fault, hence the generator can remain stable for longer periods.
- After the occurrence of a transient disturbance on the system and the generators start speeding up, the station operators try to reduce the speeding up of the generator by

reducing the excitation on the generator. If the action of the station operators fails, the over speeding protection trips the generator. The operators then wait for approximately 40 minutes for the rotor to come to a stand still before they can resynchronise the generator back onto the system. Past experience has shown that the generators normally over speeds if they were generating at full load at the time of the system fault, however the severity of the fault also plays a role.

- The generating station has no capacitor banks connected, and the generators cannot operate on synchronous condenser mode.
- Since Mbashe hydro station operates in automatic mode the station operators cannot control the amount of reactive power that is injected into the network. During a demonstration, when the station controller tried to increase the amount of reactive power injected into the system by one generator, the other generators would counteract and reduce the amount of reactive power they were supplying.
- The reliability of the generators after the occurrence of a transient disturbance was found to be poor, especially if the generators were operating at full load.

Umtata 1st Falls Hydro Power Plant

Umtata 1st falls hydro power plant has an electrical generating capacity of 6MW with two 3MW synchronous generators. The type of hydro turbine used at this station is the Francis turbine that uses a horizontal axis generator. The main components of the hydro station are the similar to those of Mbashe station. Except the flywheel is no longer separated from the generator, but it is in the same compartment as the synchronous generator.

Stability related points about Umtata 1st falls power station that were picked up while visiting the station are as follows;

- The AVR has been noticed to have a slow response by the optimisation engineers.
- As at Mbashe, synchronising of hydro generators to the network is done manually by station operators using a synchroscope. Transformer taps are used to assist the synchronising process by adjusting the system voltage, and no automatic synchronising facility is available at the station.
- When generators in the Transkei have to operate in the island operation, 1st falls is the first generating plant to operate and generate power into the load shedded network. It is the first to generate because it does not operate in the automatic mode, and critical loads that have to be supplied are located close to this hydro plant.
- Both generators can operate in synchronous condenser mode and inject reactive power into the network without utilising water (except for the little water that is used for

lubrication). The synchronous condensers are rated at 6MVAr (Two 3MVAr sets). The generators operate on synchronous condenser mode only after the instruction of the control centre in East London. The station also has capacitor banks rated at 5MVAr.

- After a severe transient disturbance on the system the generator trips, and the station operators have to wait for approximately 40 minutes for the rotor to come to a complete stand still before the generator can be synchronised back onto the system. After a transient disturbance on the system the generators are unreliable and are likely to trip.

Umtata 2nd Falls Hydro Power Plant

Umtata 2nd falls hydro power station has a generating capacity of 11MW with two synchronous generators of 5.5MW. The type of turbine used at this station is also a Francis turbine with a horizontal axis generator. In 1999 the entire hydro station got flooded which resulted in the station going out of operation for more than one year. This is because a lot of equipment got damaged. The entire hydro power station was refurbished and upgraded. The entire station control room was upgraded and new equipment was installed, including a PLC system.

Stability related points about Umtata 2nd falls power station that were picked up while visiting the station are as follows;

- After the flooding both generators were converted to operate as generators as well as synchronous condensers. A 5Mvar cap bank was removed after the flooding since the generators could now operate as synchronous condensers.
- The station operates on a fully automatic mode, with most control functions operated automatically.
- Synchronising of the hydro generators onto the network is also done automatically with a automatic synchroscope.
- A transient disturbance on the distribution network usually results in the generators tripping, and being disconnected from the system. It again takes approximately 40 minutes before the generator rotor stops and can then be re-synchronised back onto the network.
- After the flooding of the hydro plant, new 11kV SF_6 circuit breakers were installed.
- A new fast response AVR was installed after the flooding.

Ncora Hydro Power Plant

Ncora hydro power plant is the smallest power station in the Transkei. It has a generating capacity of 2.4MW with one 1.6MW synchronous generator as well as two older 0.4MW synchronous generators relocated from Umtata in 1981. The type of turbine used by the generators is a Francis turbine with horizontal generators. A visit to this station was not conducted, however the author was told that it functions very similarly to the other stations.

7.2 ASSESSMENT OF THE TRANSKEI DISTRIBUTION NETWORK

The Transkei distribution network exists in a predominantly rural area that has a maximum voltage level of 132kV and voltage levels of 66kV, 22kV, 11kV and 3.3kV. The 132kV distribution line was uprated from 66kV operation in 1990, after the Transkei load increased. Recently the Transkei network has been strengthened with another 132kV line to Kokstad. This line only came into operation in 2001. Some of the line lengths on the network are relatively long, compared to the distribution line lengths found in developed countries. For example, the longest line length is the 75.3km long 66kV line from Butterworth to Ncora.

A variety of conductor types are used on the distribution network. The conductors used on the 66kV lines include hare, wolf, rabbit, and mink (conductor data is in Appendix H). And the conductors used on the 132kV lines include wolf and hare. The conductor types used depend on the current and the load that the line is supplying. Since some of the line conductors are very long, the line impedances can be quite high and this contributes to the weak distribution network.

The Transkei distribution network has additional network components that strengthen and improve the stability of the network as well as help monitor conditions on the network. This section will present the reactive devices used on the network and then go over the protection used on the network. The island operation as well as the future plans of the network will then be covered.

7.2.1 REACTIVE DEVICES

Reactive devices that are connected to the Transkei network include capacitor banks, synchronous condensers and static var compensators (SVCs). Reactive devices play a major role in improving the stability of a network, however the manner in which they improve stability is covered in Chapter 8 in more depth.

Capacitor banks are located at First falls, Lamplough and Magwa on the Transkei network. The capacitor banks are all rated at 5MVArs and are star (ungrounded) connected. The capacitor banks inject capacitive reactive power into the Transkei network.

The generators at Umtata 1^{st} and 2^{nd} Falls can be operated as synchronous condensers. The synchronous condensers have a capacity of 6MVars and 11MVArs for 1^{st} and 2^{nd} falls respectively. The operation of the synchronous condensers occurs only after the instruction of the East London control centre.

A static var compensator (SVC) rated at 35 MVArs capacitive and 45 MVArs inductive exists at the Zimbane substation near Umtata. The SVC was installed in 1996 in order to improve the stability of the Transkei network. The Transkei network is heavily dependent on the SVC at Zimbane substation, especially during peak loads. In the event that the SVC is disconnected from the system during peak periods, the network would suffer voltage stability problems. This is because during peak periods all the hydro power plants are in generation mode, and are not used as synchronous condensers.

7.2.2 PROTECTION

The type of protection used on the Transkei network includes over current protection, earth fault protection and distance protection. The network utilises single pole as well as three pole auto reclosing. Protection on the distribution network is one of the most important operations because it determines how long a fault lasts on the distribution network. If a fault is cleared quickly, this is beneficial to the network stability. And if a fault is not cleared quickly, this could have detrimental effects on the system stability. This is because when a fault is not cleared quickly the generators that are connected to the network could lose their stability, which could result in the generators being disconnected from the system. The disconnection of the generators could lead to voltage levels on the system being affected. It is hence clear that if a fault on a system is not cleared quickly the system stability is affected, which is why protection is an important operation when considering the stability of a system.

Auto Reclosing

The operation of the auto reclosers play an important role in the stability of a distribution network because after the occurrence of a transient disturbance the auto reclosing can reconnect poles if the fault no longer exists. Since the majority of short circuits are single line to ground, independent-pole circuit breakers can be used to clear a faulted phase while keeping the unfaulted phases of a line operating, thereby maintaining some synchronising power transfer across the faulted line. This can again be beneficial to the stability on the network.

The Transkei network utilises single pole as well as three-pole auto reclosing, as mentioned above. The single pole auto reclosers are located on the 132kV lines, and they do not exist on the 66kV lines. They do not exist on the 66kV lines due to the relatively high cost of single pole auto reclosers at this voltage level. The three pole auto reclosers are located on the 66kV lines. The operation dead time of the single pole auto reclosers range from 300msec to 500msec and the operation dead time of the three-pole auto reclosers range from 2 to 4 seconds.

Over Current and Distance Protection

The Transkei network also utilises over current as well as distance protection in order to clear faults that would damage network components as well as electrical equipment connected to the network. The next section of this chapter carries out a stability study on the Transkei network and critical fault clearing times (CCT) of all the generators connected to this network are established. It is important that distance protection and over current protection is able to clear faults before the CCT of the generators, depending on the fault location. This is because if the fau lt lasts for longer than the CCT of the generator it is possible that the generator will lose its stability.

7.2.3 VOLTAGE REGULATORS

Eight voltage regulators currently exist on the Transkei network. The voltage regulators are only installed on the 22kV distribution lines and are rated at 100 amps. The voltage regulators assist with voltage control on distribution networks, by stepping up the voltage when the voltage drops below the regulated values. They are installed on the 22kV network due to cost constraints. Small voltage regulators are not very costly, therefore the utility can afford to use voltage regulators at 22kV to improve voltage levels. No voltage regulators are installed at 66kV because the voltage regulators at this voltage level are very costly.

7.2.4 ISLAND OPERATION

The Transkei Network sometimes operates in an islanded operation. This would occur if there is no supply from the Eskom grid, hence portions of the Transkei network would be supplied by the hydro generators that exist within the network. This would normally occur if there were lightning storms or faults in the region, which have resulted in no supply from the Eskom grid. When the Transkei network has to operate as an island the following procedures are followed;

- First falls is the first station to operate because this station is operated manually. It then supplies essential loads at Umtata.
- Second falls is then synchronised with First falls, and more loads are connected to the island.
- Mbashe as well as Ncora are then synchronised with the island, and then more loads are connected depending on the generating power from the hydro stations.

When the Eskom supply is reinstated, the island is synchronised with the Eskom grid. It is synchronised using auto-synchronising equipment that is located at the 132kV substations. One of the Auto-synchronising devices is located at the Zimbane 132kV sub station.

7.2.5 FUTURE NETWORK PLANS

Voltage control on the Transkei Network raises concern for the future. Currently the Transkei network relies on transformer taps, capacitor banks, reactive power from hydro generators, synchronous condensers and static var compensators for controlling voltage on the system. With the increase in load in the region, the control centre at East London has been experiencing voltage control problems due to an imbalance in reactive power on the system. This problem frequently occurs when the load is at its peak, which results in some lines being overloaded. The recently constructed 132kV line to Kokstad gets overloaded from time to time, hence the control centre has voltage control problems on this line. There are plans to install two 18MVAr capacitor banks at Kokstad in the near future for voltage compensation. This is because capacitor banks are the cheapest method of injecting reactive power in order to control the voltage on the line.

After the visit to the hydro station it was revealed that there are plans to upgrade the AVRs at First falls hydro station. These AVRs are to be upgraded due to their slow response after a system disturbance. Fast response exciters will improve the transient stability of the hydro generators and hence improve the transient stability of the network.

7.3 TRANSIENT STABILITY STUDY OF TRANSKEI NETWORK

This section presents transient stability studies that were carried out in order to highlight issues raised by the connection of the Transkei hydro generators to the Transkei distribution network. This study is different from the other studies that were conducted in earlier chapters because the generators in this distribution network are connected in parallel (i.e. more than one generator connected to a bus bar). This study seeks to investigate the transient stability of the Transkei network and focusing on the following;

- Critical fault clearing time (CCT) of generators without governors
- CCT of generators with governors

The purpose of removing the governors and later replacing them is to investigate the impact of the governor controllers on the transient stability of distribution networks with DG.

7.3.1 NETWORK DESCRIPTION

The complete Transkei distribution network was simplified into a smaller network that consists of 21 bus bars, 10 transformers, 8 lines and 4 voltage levels (132kV, 66kV, 22kV and 11kV), as shown in Figure 7.4. The Transkei network was simplified because the version of Digsilent used by the author is limited to 35 bus bars, and the complete Transkei network could not be simulated. The simplification of the network does not alter the stability studies' objectives, but instead leads to an increased understanding of the study because the study is performed on a smaller network.

The Transkei network was recently reinforced by linking it up with the Kwa-Zulu Natal network. This was done by constructing a 132kV line from Zimbane to Kokstad in 2001. This line was not modelled in the network used for the stability studies because it was recently constructed and is apparently not always connected. Also not modelled is the SVC at Zimbane sub-station.

The majority of the network exists in rural areas, and generally consists of radial networks. The loads are connected to the 66kV, 22kV and 11kV voltage levels, and an external grid supply point is connected to the 132kV voltage level.

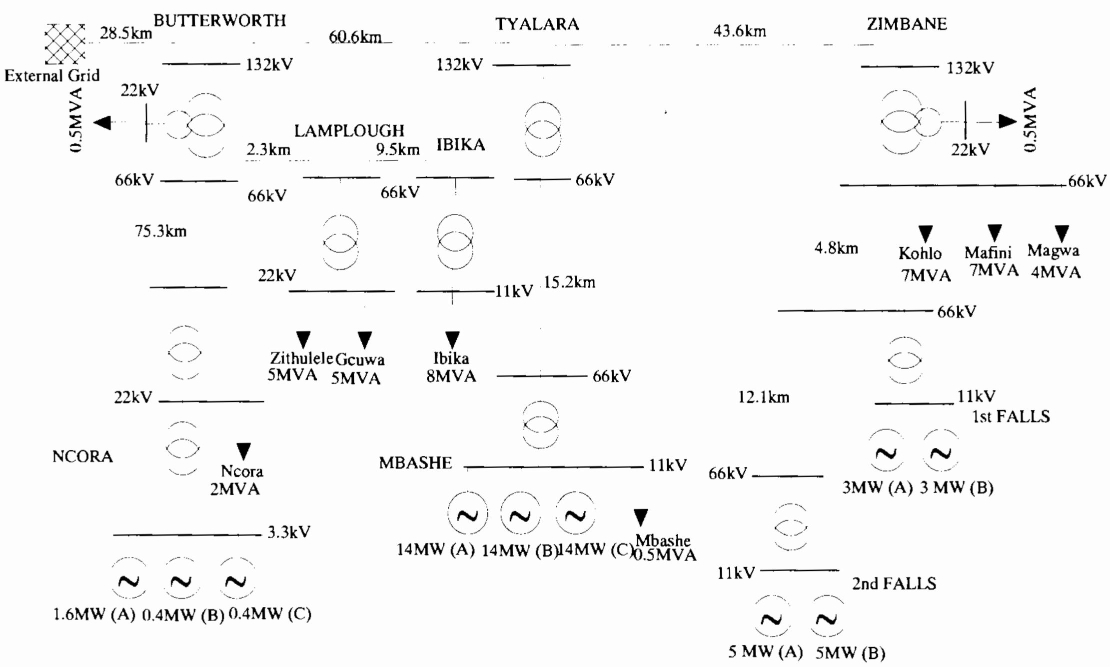


Figure 7.4: Single line diagram of a simplified Transkei network

7.3.2 GENERATORS

Ten hydro generators that are synchronous machines are connected to the Transkei distribution network. The generators are all connected with automatic voltage regulators (AVR), and the data for the AVRs is listed in Appendix C. In the second part of the study the generators are connected with governors, the data for the governors is listed in the Appendix C. The power ratings of the hydro generators are listed in Table 7.1.

7.3.3 LOAD MODEL

The different load centres that need to be modelled are illustrated on the Transkei network in Figure 7.4, and they include Butterworth, Ncora, Zithulele, Gcuwa, Ibika, Mbashe, Kohlo, Mafini and Magwa. The load in Butterworth and Ibika is predominantly industrial. According to a load survey done for the Transkeian government, the energy used in Kohlo, Mafini and Magwa was approximated as shown in Figure 7.5; [52]

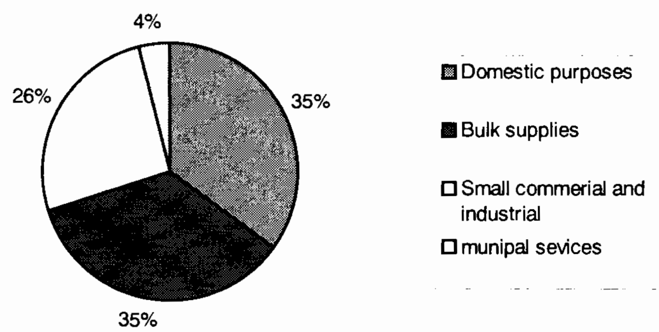


Figure 7.5: Electrical energy used by different classes of consumers in Kohlo, Mafini, Mbashe, Gcuwa, Ncora, Zithulele and Magwa

As mentioned earlier, in order to maintain simplicity on the Transkei network some portions of the network were lumped into single loads. These portions of the network consisted of residential, industrial, and commercial consumers. The load model that was modelled on the simplified Transkei network was a mixture of static and dynamic loads. Sixty percent of the load model was static and forty percent of the load model was dynamic.

7.3.4 DISTURBANCE

The type of disturbance that was inflicted on the distribution network is a three-phase fault. The three-phase fault was introduced on to the generator terminals of the four generating stations, in order to establish the lowest critical fault clearing time of the generators.

7.3.5 LOAD FLOW STUDY

A load flow diagram of the Transkei network is shown in Appendix C. The load flow results of the Transkei network show that 20.11MVAr of reactive power is imported from the external grid. The active power supplied by the hydro generator is sufficient to supply the entire Transkei network, to the extent that 9.12MW is exported to the external grid. The voltage levels on all the bus bars are within 10% of the nominal voltage.

7.3.6 SIMULATION

Since the objective of the stability studies in this chapter is to investigate transient stability of the hydro generators with and without governor controllers, the simulations were separated in two parts. The difference between the two parts is that the hydro generators in the first part were not connected with governor controllers, and the hydro generators in the second part were connected with governor controllers. The method of investigation for the two parts when carrying out transient stability studies was the same.

In each simulation part the critical fault clearing time (CCT) of the hydro generators was established. This was after a three-phase fault had been introduced on the bus bar to which the generators are connected. The critical fault clearing times of the hydro generators were then compared and analysed. The relative speed, rotor angle, excitation voltage and turbine power of the generators was monitored.

It must be noted that at each hydro station the generators are either labelled A, B or C, as shown in Figure 7.4. The difference between the generators is the mode of the local voltage controllers. The generator that is labelled A has a local voltage controller that controls the bus voltage. And the generators that are labelled B and labelled C have a local voltage controller that controls the power factor. When analysing the results, the A labelled generator will be compared to the B or C labelled generators because the mode of operation of the voltage controller of the B and C labelled generators is the same.

RESULTS OF TRANSIENT STABILITY STUDIES WHEN HYDRO GENERATORS ARE NOT CONNECTED WITH A GOVERNOR

It must be noted from Figure 7.4, that CCT A, CCT B and CCT C respectively refers to the Critical fault clearing times of the A, B and C labelled generators, and the critical fault clearing times for the different generators are for the worst case fault position and they are not all for the same fault position. Therefore in order to determine CCT A, CCT B and CCT C for the Ncora generators a three-phase fault was introduced onto the terminals of the Ncora generators, and in order to determine CCT A, CCT B and CCT C for the Mbashe generators a three-phase fault was introduced onto the terminals of the Mbashe generators, and so on.

Hydro Station	CCT A /msec	CCT B /msec	CCT C /msec
Ncora	211	212	212
Mbashe	194	230	230
1st falls	232	235	-
2nd falls	252	261	-

Table 7.2: Critical fault clearing time results for the hydro generators (with no governor) connected to the Transkei distribution network

The results from the above table show that all the generating stations have different critical fault clearing times for the different generators (bearing in mind that the comparison is being made between the A labelled generator and the other generators). The generating stations have different CCT results for the different generators due to the influence of the different modes of the voltage controllers. It is noticed that the A labelled generators always have a lower CCT value compared to the B or C labelled generators. The B and C labelled generators always recorded similar values of CCT.

The hydro generators at Ncora hydro station have a different scenario compared to the generators at the other stations because the generators at this station do not have similar power ratings. The A and C labelled generator at the Ncora generating station were found to have a critical fault clearing time of 211msec and 212msec respectively. When a three phase fault with a fault duration of 211msec was introduced on the terminals of the A labelled generator at Ncora, Figure 7.6 and Figure 7.7 show that the rotor speed of the smaller C labelled generator (0.4MW) recorded the highest speed and its rotor angle swung 3 times between +/- 180 degrees before recovering. When analysing these graphs, the smaller C labelled generator looks as if it will lose stability first due to the higher speed values recorded and the high swinging of the rotor angle. This is however not the case because after a fault duration of 212msec the A labelled generator lost its stability, and the C labelled generator lost its stability after a fault duration of 213msec as shown by Figure 7.8. Even when the B or C labelled generator was a smaller generator, the A labelled generator lost its stability first. However it must be noted that the 2msec difference is not significant.

Figure 7.8 shows that when no governor is connected the rotor speeds consistently rise when the generators lose stability. This is caused by the fact that the turbine power (mechanical power input) remains constant even after the generator loses stability and supplies no load. More simulations results are shown in Appendix C.

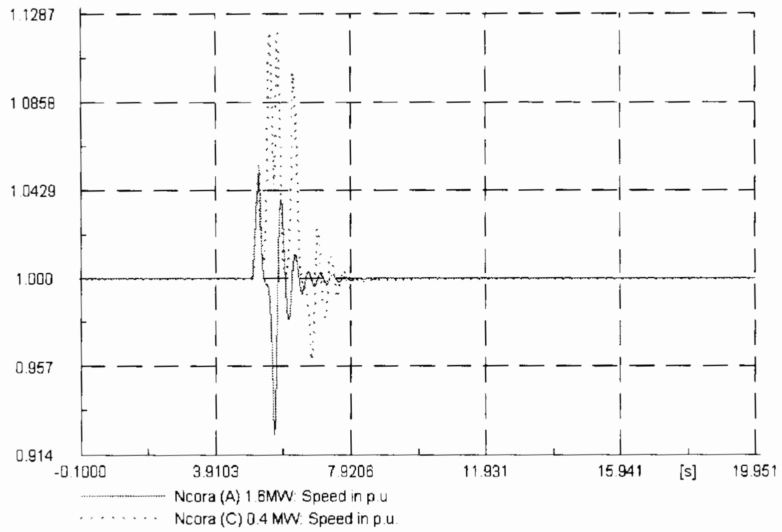


Figure 7.6: Rotor speed of hydro generators at Ncora after a 3 phase fault dt=211msec

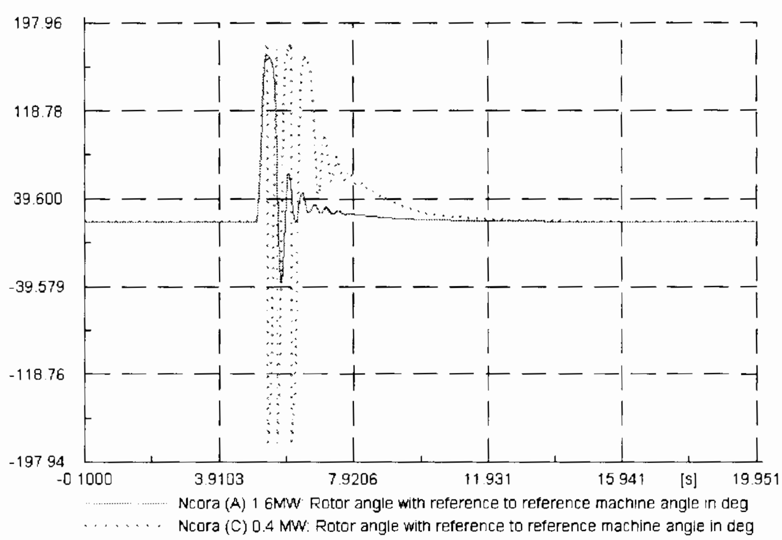


Figure 7.7: Rotor angle of the hydro generators after a 3 phase fault at Ncora dt=211msec

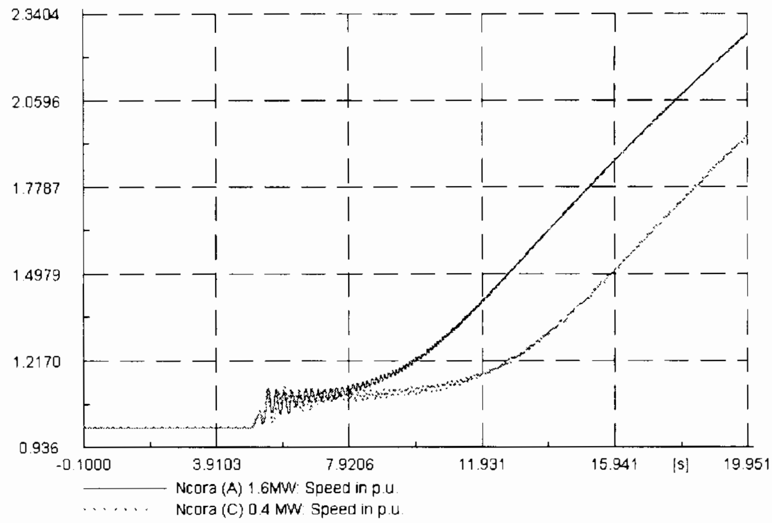


Figure 7.8: Rotor speed of the hydro generators with no governor after 3 phase fault at Ncora dt=213msec

At Mbashe generating station the A labelled generator lost its stability first, this was after a three-phase fault duration of 195msec at the terminals of the generator. The B and C labelled generator lost its stability after a three-phase fault duration of 231msec. The generators at this hydro station all had the same power rating. Again the A labelled generator which has a voltage controller that controls the bus voltage lost its stability first compared to the B and C labelled generators that have voltage controllers that control power factor.

The critical fault clearing times between the A labelled generator and the B and C labelled generators at Mbashe is quite significant compared to the Ncora hydro generators. This time there was a 36msec difference. One of the obvious differences between these two types of hydro stations is the power rating of the generators, the generators at Mbashe have higher power ratings. Another difference that exists is the electrical strength of the connection to the grid. The rotor angle and excitation voltage graphs can also be used to explain the significant difference in CCT times of the generators.

Figure 7.9 which shows the excitation voltage of the hydro generators at Mbashe after a three phase fault duration of 194msec at the terminals of the generators, shows that the excitation voltage of the A labelled generator is less than half the excitation voltage of the C labelled generator before the fault occurs. During the three-phase fault the excitation voltage of the A labelled generator dropped to 0pu, and the C labelled generator dropped momentarily to an excitation voltage of approximately 0.8pu. The dropping of the excitation voltage to zero might have been one of the contributing factors that resulted in the A labelled generator losing its stability significantly faster than the B and C labelled generator. One wonders whether this is as a result of the model, and if this would happen in practice.

Figure 7.10 illustrates the rotor angles of the generators at Mbashe before and after the three-phase fault duration of 194msec. It shows that the rotor angle of the A labelled generator shot up to approximately 165 degrees after the 194msec three-phase fault duration, and the C labelled generator only shot up to a maximum of 110 degrees. Which is why after a fault duration of 195msec the generator labelled A lost its stability and the generator labelled C was able to recover. The C labelled generator only lost its stability after a three-phase fault duration of 231msec, therefore meaning that it had a CCT of 230msec. More simulation results are shown in Appendix C.

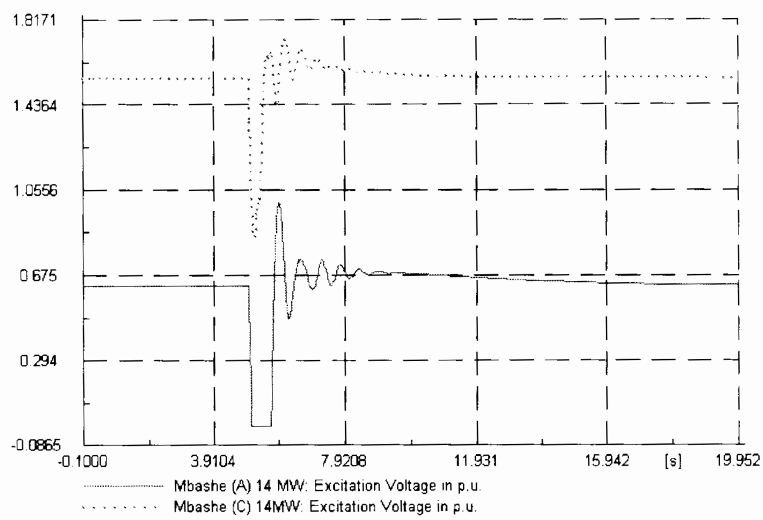


Figure 7.9: Excitation voltage of hydro generators at Mbashe after a 3 phase fault dt = 194msec

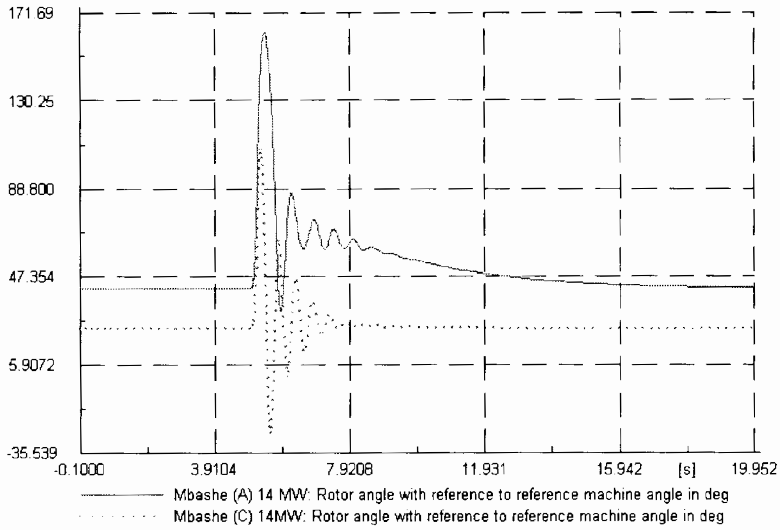


Figure 7.10: Rotor angle of hydro generators at Mbashe after a 3 phase fault dt = 194msec

The generators at the first falls generating station had critical fault clearing times of 232msec and 235msec for the generators labelled A and B respectively. The two types of generators were rated at the same power rating and they had similar electrical parameters. The excitation voltage of the A labelled generator was approximately 20 percent lower than the excitation voltage of the generator that was labelled B. The different starting conditions were caused by the different operational modes of the local voltage controllers. The A labelled generator again lost its stability first when a three phase fault of duration 233msec was inflicted on the terminals of the generators. The B labelled generator lost its stability after a three-phase fault duration of 236msec on the terminals of the generator. There is no significant difference in the critical fault clearing times between the two types of generators. More simulation results are shown in Appendix C.

At the second falls generating station the A labelled generator again lost its stability first, this was after a three phase fault duration of 253msec at the terminals of the generators. The B labelled generator lost its stability after a three-phase fault duration of 262msec. Even at this generating station the A labelled generator had an excitation voltage that was 25 pecent lower than the excitation voltage of the B labelled generator. Both the generators at this hydro station had the same power ratings as well as electrical parameters. More simulation results are shown in Appendix C.

RESULTS OF TRANSIENT STABILITY STUDIES WHEN HYDRO GENERATORS ARE CONNECTED WITH A GOVERNOR

It must be noted again that CCT A, CCT B and CCT C refers to the generator that has a label A, Label B and label C respectively as shown in the single network diagram in Figure 7.4, and critical fault clearing times for the different generators are for the worst-case fault position and they are not all for the same fault position.

Hydro Station	CCT A /msec	CCT /msec	CCT C /msec
Ncora	209	209	209
Mbashe	192	228	228
1st Falls	228	233	-
2nd Falls	250	259	-

Table 7.3: Critical fault clearing times for the hydro generators (with a governor) connected to the Transkei distribution network

The results above show that the inclusion of the governor controller to the hydro generators does not significantly change the critical fault clearing time results obtained in the previous part in which the governors were not connected. Instead, all the critical fault clearing time results slightly decreased by a small margin. The governor therefore had the same effect on almost all the generators. This result was expected, because the governor controls the guide vanes of the generator and its speed is not expected to be fast. However a study by Edwards et al [10] revealed that a governor has a great effect on the inherent damping of the generator. It is hence essential that a hydro generator be fitted with a governor in order to control the speed and damping of the hydro turbine under different conditions. The governor hence has an impact on the small signal stability of the hydro generator.

Some of the features of governors include:

- Speed control of the hydro-turbine under different conditions of start-up and load fluctuations
- Fast response to load imposition and load rejection
- Shutting down inlet valve in case of over speed tripping

Some of these features were observed while carrying out stability studies on the Transkei distribution network. The most prominent feature that was observed was the speed control of the hydro turbine under different conditions. The governor was able to limit the speed of the hydro rotor from reaching extremely high speeds. This is illustrated by Figure 7.11 which shows the governor limiting the rotor speeds to less than 1.125p.u. for a 213msec three phase fault, whereas for the same fault without a governor the rotor speeds constantly increased. An added advantage of using the governor was the shutting down of the inlet valve in case of over speeding. This is shown in Figure 7.12, where the turbine power was reduced to zero when the rotor was over speeding. When the turbine power was reduced to zero the rotor angle was forced to settle down to a rotor angle of zero, because the mechanical power input was also zero.

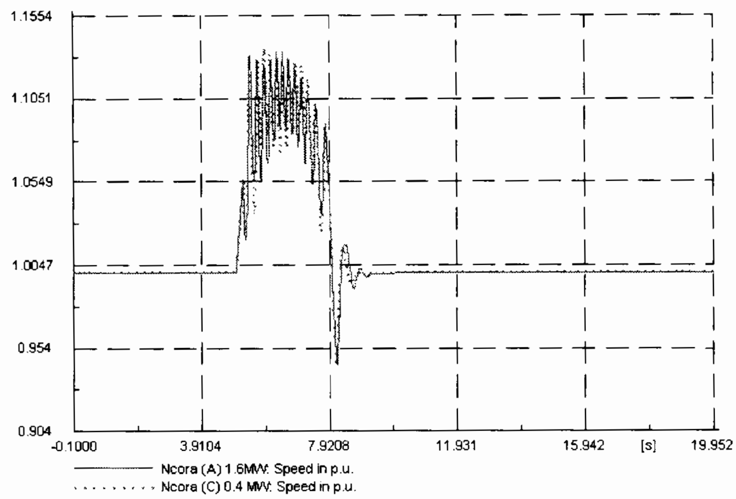


Figure 7.11: Rotor speed of the hydro generators with a governor after 3 phase fault at Ncora dt=213msec

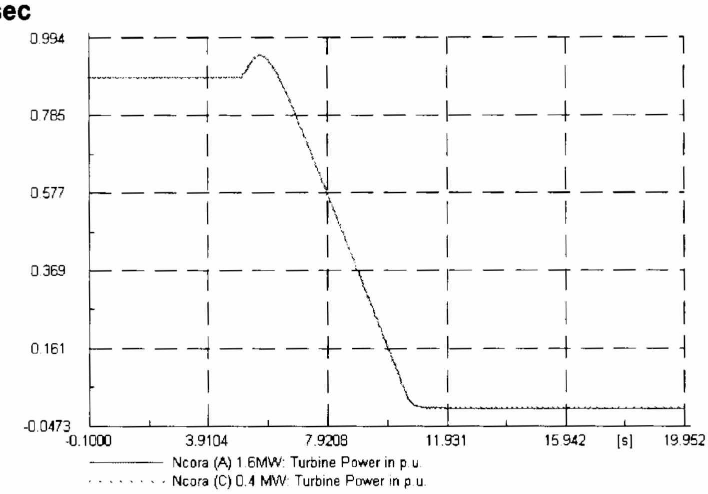


Figure 7.12: Turbine power of the hydro generators with a governor after a 3 phase fault at Ncora dt = 213msec

7.3.7 ANALYSIS OF RESULTS

The stability studies that were conducted in this case study have revealed the following key results for generators that are connected in parallel and having one generator operating as a local bus voltage controller and one or more generators controlling the bus power factor:

- The governor control does not significantly impact the transient stability of hydro generators, even though it improves conditions that would lead to the instability of the hydro generator (e.g. generator speed).

- When generators are connected in parallel they do not all lose stability at the same time, even when they have similar power ratings. This is caused by the fact that the generators have different voltage controller modes.
- The mode of operation of the voltage controller can affect the transient stability of hydro generators. To some extent this is dependent on the excitation voltage of the generators.
- The fastest protection that must be used on the Transkei network has to operate within 192msec in order to protect one of the Mbashe hydro generators. This would be after the worst-case fault on the terminals of the Mbashe hydro station. This operation time is not very practical. However considering the fact that some of the generator parameters were estimated, it is possible that the CCT times are too low. Distance protection would not have a problem with clearing faults before the CCT, but over current protection would battle. But most importantly the location of the fault would determine whether the fault is cleared by over current protection or distance protection.

7.4 SUMMARY OF TRANSKEI NETWORK STUDY

A stability study of the Transkei Network that is connected with hydro generators has been presented. This study included theoretical results as well as practical results that were obtained from a visit to the Transkei. The study started by presenting the distributed generation stations and the network they are connected to. This was done in order to give a holistic perspective to the study, and tie the theoretical as well as practical aspects together. While presenting the hydro stations located in Transkei, stability related aspects that were picked up while visiting the station were discussed.

The hydro generators located in Transkei comply with the distributed generation definition that was presented in chapter 2, and can be considered as typical examples of distributed generation. The generation schedule of the hydro generators was found to be mainly controlled by the availability of water, which is limited during the dry season. Depending on the availability of water, the generators operate 24 hours in the rainy season and during peak hours in the dry season.

After a visit to the hydro stations, It was gathered that the hydro generators in Transkei were unreliable after the occurrence of transient disturbances on the system. This was however determined by the location of the disturbance and the percentage loading of the generator. The theoretical results revealed that the CCT times of the Transkei generators were less than 260msec. If the disturbance was relatively close and the hydro generator was operating at full load, the generators would be likely to lose stability which would result in the generator tripping and the operators having to wait for 40 minutes before the generator can be resynchronised back onto the system. The speed of the excitation system on all the hydro generators except the 2nd

falls station were found to be slow, which has resulted in optimisation engineers proposing to install faster excitation systems on the hydro generators.

The Transkei distribution network was found to have reactive devices as well as protection systems that would improve the stability of a network. The network was also installed with capacitor banks, synchronous condensers and static var compensators that inject reactive power into the system in order to improve stability on the network, by injecting capacitive reactive power into the system when there is a high demand of inductive reactive power. The provincial control centre in East London controls the operation of these reactive devices. Protection of the netw ork is one of the important operations that can determine the stability of the distribution network. Over current and distance protection used on the Transkei network should be able to clear a fault before the generators reach the CCT, depending on the fau lt location. In the near future, capacitor banks will be installed in Kokstad in order to improve the voltage control on the network, since it has been identified as a problem. The installation of the capacitor banks can only be a short-term solution.

The transient stability studies that were conducted revealed the critical fault clearing times of all the hydro generators with and without a governor. The CCT is useful when setting the protection times. The governor controller was also found not to signifi cantly improve the critical fault clearing time of the hydro generator, however it is important that a hydro generator be fitted with a governor in order to control the speed of the hydro turbine under different condition. It was also established that when generators are connected in parallel they do not all lose their stability at the same time.

When comparing the theoretical results with the practical results, it is realised that the protection that exists on the Transkei distribution network is not ab le to clear faults in time for the generators to stay connected to the network. The electrical weakness of the Transkei network must also not be overlooked. The coordination between equipment protection/controls and power system requirements should be reviewed. This is however influenced by the loading of the generators as well as the location of the transient disturbance. However, it was discovered that the reliability of the generators after the occurrence of a severe disturbance on the distribution netwo rk is poor. The critical fault clearing times of the generators that are located in the Transkei were established to all fall below 260msec, and from the reliability results just discussed, it is evident that the some protection is not able to clear the fa ults before the critical fault clearing times of the generators. However this is determined by the location of the fault, and whether over current or distance protection is installed.

CHAPTER 8

IMPLICATIONS OF POTENTIAL INSTABILITY AND WAYS OF IMPROVING STABILITY

This research has revealed that the stability of distribution networks that are connected with distributed generation is an area of study that cannot be overlooked, especially in weak distribution networks. The two forms of stability that have shown to have a large impact are transient stability and voltage stability. In the event that a distribution network connected with distributed generation becomes transiently unstable or voltage unstable, how does this impact the distribution network? And what are the different ways that can be used to improve stability on the distribution networks that are connected with distributed generation? These are the questions this chapter seeks to address.

This chapter is divided into six sections. The first section presents the implications of potential transient and voltage instability on a distribution network. The second section presents instability of distribution networks that need DG for voltage support. The next section covers methods of improving transient stability, and the fourth section presents methods of improving voltage stability and preventing voltage collapse. The fifth section presents recommendations for the Transkei network. Lastly, the chapter is summarised.

8.1 IMPLICATIONS OF POTENTIAL INSTABILITY

The loss of stability on a distribution network can result in voltage profiles on the distribution network exceeding the required limits and conditions of quality of supply being violated. This however depends on the type of instability on the distribution network. The different types of instabilities studied for these distribution networks include transient instability and voltage instability. The effect of large disturbances on weak distribution networks, which are typically found in Southern Africa, is relatively greater than distribution networks from developed countries as discovered in the stability studies. In this chapter the implications of instability on quality of supply is assessed.

8.1.1 TRANSIENT INSTABILITY

Transient instability is concerned with the inability of the power system to maintain synchronism when subjected to a severe disturbance. As mentioned in chapter 4, the factors that affect the transient stability of a power system include [4]:

- The strength of the network
- The characteristics of the generating units, including the inertia of the rotating parts and such electrical properties as transient reactance and magnetic saturation characteristics of the iron in the stator and rotor
- The speed at which the faulted lines or equipment can be disconnected from the system and how rapidly the lines can be restored to service by automatic reclosing of the network line
- The speed at which the generator excitation system responds, since disturbances are usually accompanied by rapid reductions in system voltage and rapid restoration of the system voltage to normal is important in maintaining stability

After a severe large disturbance on a distribution network that causes a synchronous generator to go into a state of instability, the generator will pole slip and will lose synchronism with the distribution network. According to Redfern and Checksfield [44], pole slipping causes dramatic fluctuation of the generator's currents and as a result can cause fluctuations in the distribution networks' voltage. Generators that are under-excited can also increase the occurrence of pole slipping. This is because under excitation reduces the maximum electrical power that can be taken out of the generator. From a machine point of view, pole slipping occurs when the mechanical torque produced by the prime mover is greater than the electromagnetic torque used to produce the power output. If this condition continues for too long the rotor is unable to stay in synchronism with the stator magnetic flux.

When the synchronous generator pole slips and the generator is not disconnected, power quality standards are violated. This is because the high currents that are associated with pole slipping can cause voltage fluctuations to the local network, hence motor starter contactors connected to the network will open and induction motors will stall. This impact of pole slipping is greater on bus bars that are close to the unstable generator.

When the voltage profile of a synchronous connected bus bar was monitored during pole slipping in case study 1, voltage fluctuations were evident, as shown in Figure 8.1. This was after the introduction of a three-phase fault on the terminals of the synchronous generator. The fault was introduced after 5 seconds of simulation and was cleared at 5.1783 seconds. The critical clearing time of the synchronous generator was found to be 178.2 msecs. Figure 8.1 clearly shows that the synchronous generator pole slipping results in voltage fluctuations on the local network. Before the voltage fluctuation occurs, the voltage of the bus bar is depressed to zero volts (during the 178.3msec three-phase fault). The voltage then fluctuated between approximately 0.7 and 0.25p.u. Pole slipping starts occurring after the voltage dips down to approx. 0.17 pu at 5.7 secs. When it starts pole slipping the voltage magnitude approximately fluctuates at 20 Hz. This type of fault would possibly be cleared by the over speed protection of the generator. The voltage profile shown in Figure 8.1 clearly violated the power quality standards, and it is voltage waveforms like this one that causes induction motors to stall and motor starter contactors to open. The power quality standard that was violated in this case is the voltage regulation standard, where according to NRS 048-2 [45], the voltage is suppose to be kept at +/- 10% of the declared voltage.

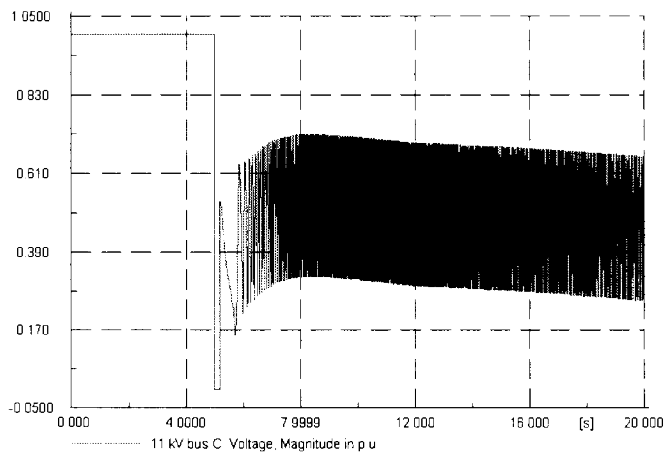


Figure 8.1: Voltage profile of a 11kV bus bar after a synchronous generator pole slipped and lost synchronism

After the occurrence of a large disturbance on a distribution network induction generators are likely to over speed and go over the critical stability limit. This is influenced by the duration and magnitude of the disturbance. When an induction generator goes over its critical stability limit the generator continuously speeds up until it is disconnected from the network. The protection on the distribution system should disconnect the unstable generator as soon as it is unstable. When the induction generator speeds up it draws large amounts of reactive power from the network. Most of the issues that arise when an induction generator loses its stability pertain to voltage instability, and these issues are discussed in the next section.

8.1.2 VOLTAGE INSTABILITY

Voltage instability is concerned with the inability of a power system to maintain steady acceptable voltages at all bus bars in the system under normal operating conditions and after being subjected to a disturbance. As mentioned in chapter 4, the main factor causing voltage instability on a distribution network is the inability of the network to maintain a proper balance of reactive power throughout the system. Voltage instability may occur in the form of a progressive fall or rise of voltage of some bus bars.

Since the main factor that is likely to give rise to voltage instability on a distribution network is the inability of the network to maintain a proper balance of reactive power throughout the system, only generators that utilise induction generators are likely to pose a threat to the voltage stability of a distribution network. This is because synchronous generators can independently control the reactive power they input into the network. Whereas induction generators require reactive power from the network in order to operate, and during large disturbances they draw large amounts of reactive power.

Figure 8.2 shows a typical case of an induction generator drawing large amounts of reactive power when in a state of instability. This was after a three-phase fault duration of 1151msec and power production of 70%. The critical stability limit of the induction generator was established to be 1150msec. This figure shows that the reactive power demand of the induction generator increased by approximately 700%. Therefore if a distribution network has a high penetration of induction generators and it is a weak network, the occurrence of a large disturbance on this network will likely result to voltage instability. This may lead to a progressive fall or rise of voltages on the bus bars. If the voltage does not progressively fall or rise on the network, the steady state voltage of some bus bars could be reduced or increased by a big margin. This observation was monitored in Chapter 6 and is shown in Figure 8.3. Since the fault duration is 1151msec the generator loses its stability and continues to draw large amounts of reactive power (since it is not disconnected). The voltage profile of the bus bar to which the generator is connected to firstly gets depressed to zero during the fault, then it settles at a voltage level lower than the nominal value due to the reactive power demand of the induction generator. If the induction generator were to be disconnected when it loses stability the voltage profile of the bus bar to which it is connected would return to the nominal value.

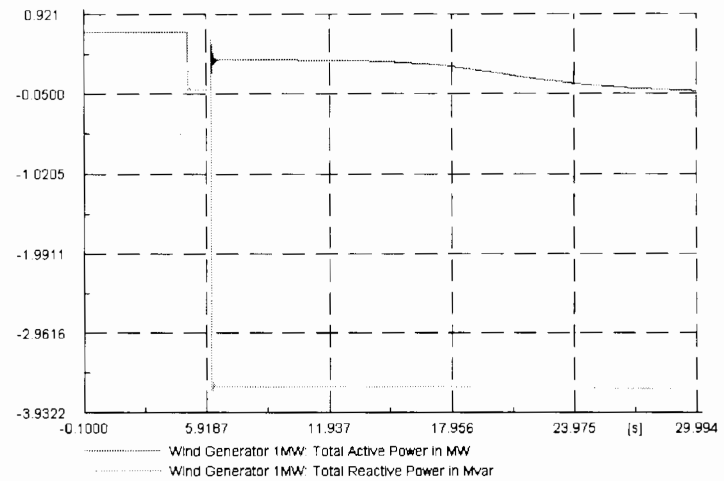


Figure 8.2: Active and reactive power of the induction generator after a fault duration of 1151msec and power production of 70% (case study 4)

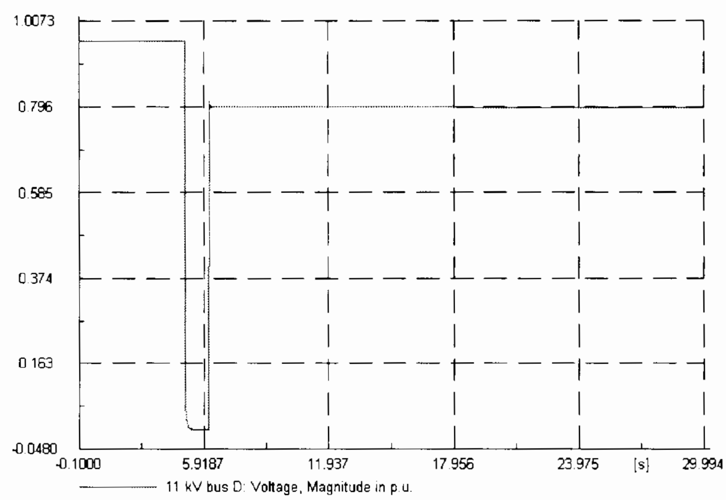


Figure 8.3: Voltage profile at 11kV bus bar D after fault duration of 1151msec and power production of 70%

If the network that the induction generator is connected to is electrically weak and there is a very high demand of reactive power from loads as well as the unstable induction generators, the voltage at the bus bars is likely to collapse. Case study 4 (chapter 6) demonstrated a similar case, and this resulted in a progressive fall in voltage as shown in Figure 8.5.

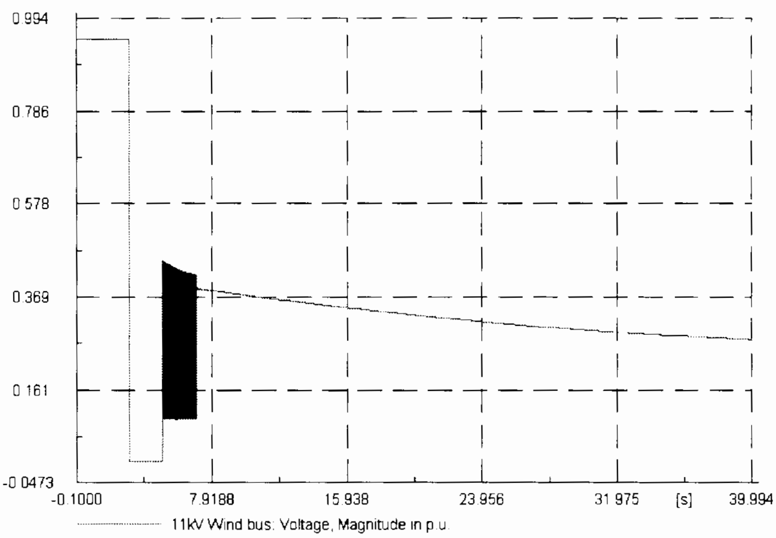


Figure 8.4: Voltage profile at 11kV wind bus after a three phase fault and the disconnection of a hydro generator on a weak network

It was clear from the stability studies that were undertaken that when the induction generator loses stability it draws large amounts of reactive power, which can lead to the depression of voltage levels. If the induction generator is not disconnected from the network very quickly this can result in a progressive fall of voltage or voltage collapse depending on the electrical strength of the network. The implication of this would not be favourable to a customer and power quality standards would be violated.

8.2 INSTABILITY OF DISTRIBUTION NETWORKS THAT NEED DG FOR VOLTAGE SUPPORT

One method of improving voltage regulation of an extremely weak distribution network is to connect a distributed generator. By doing this, the distributed generator would provide voltage support and system strengthening. A typical example is an electrically weak long radial feeder that experiences voltage regulation problems towards the end of the feeder due to an increase in load on the feeder. It is important to realise that the stability of such networks after the occurrence of a transient disturbance is extremely poor, even though a DG has been added for voltage support. This section seeks to clarify the reasons why the stability of extremely weak networks connected with DG is extremely poor.

8.2.1 CATHEDRAL PEAK NETWORK

One example of an extremely weak network in Southern Africa is the Cathedral Peak network. The Cathedral Peak network is located in the northern Drakensberg, and has a nominal voltage of 11kV. The network has a radial network that is 41km long. Due to a considerable load growth in the area in the form of electrode boilers (for both the local mission hospital and nurseries) an excessive voltage regulation problem towards the end of the network resulted. In order to improve the voltage regulation problems a 500kVA synchronous diesel generator is synchronised with the network, and the system voltages are dramatically improved. Even though the diesel generator provides voltage support and to some extent strengthens the network, the network remains a weak network due to the long high impedance line. Therefore changes in both active and reactive power have significant effects on the steady state voltage changes. After the occurrence of a transient disturbance on such a network voltage fluctuations occur on the entire radial network.

8.2.2 STABILITY OF GENERATORS USED FOR VOLTAGE SUPPORT

The stability of distributed generators that are used for voltage support on weak networks can be assessed in general terms with very simple analysis. When a transient disturbance is introduced onto the weak network, the generator is most likely to lose its stability due to the fact that the network on its own is unable to support itself. Therefore when the perturbation occurs the generator tries to stabilise itself while the conditions on the weak network get worse, which results in the generator losing its stability and the whole network destabilising due to the unavailable DG support and impact of the perturbation. When the distributed generator loses its stability it would be disconnected from the network.

It is therefore evident that extremely weak networks that are connected with distributed generators for voltage support are bound to have stability problems when transient disturbances occur on their networks. Therefore networks such as Cathedral peak will have stability related problems. A solution to this problem would be to upgrade the network and improve the strength of the network, thereby reducing the network impedance. This would however be a costly exercise.

8.3 IMPROVING TRANSIENT STABILITY

There are a number of methods and applications that can be done to improve the transient stability of distribution networks. These methods include high-speed fault clearing, regulated shunt compensation, dynamic braking, fast responding high gain exciters and reactor switching.

The different methods try to reduce the disturbing influence by minimising the fault severity and duration. They also try to increase the restoring synchronising forces, as well as reducing the acceleration torque by applying artificial load or control of prime mover mechanical power. Large disturbances on distribution networks cannot be avoided and are a big threat to the stability of distribution networks with DG. Ideally the interconnection of distributed generation should not degrade the stability of distribution networks, but instead should improve it. Some of the methods of improving transient stability on distribution networks that are connected with DG are covered in this section.

8.3.1 HIGH SPEED FAULT CLEARING

The amount of kinetic energy gained by the generators during a fault is directly proportional to the fault duration; the quicker the fault is cleared, the fewer disturbances it causes [31]. Protection fault clearing times on distribution networks are often in the order of 500msecs – 1.5secs, however this would depend on the protection settings. As observed in this thesis, critical fault clearing times of distributed generators can often be lower than the clearing times of typical distribution protection. Therefore if high-speed fault clearing occurs the generators would be able to recover from the fault. This would require fast protection relays with a speed of the order of at least 300msecs. High-speed fault clearing would also improve the power quality of the distribution network because voltage depressions can be reduced.

8.3.2 REGULATED SHUNT COMPENSATION

Two types of shunt compensation that can be used to improve transient stability include synchronous condensers and static var compensators. Shunt compensation capable of maintaining voltages at selected points on the distribution network can improve stability by increasing the flow of synchronising power among interconnected generators. [31]

SYNCHRONOUS CONDENSERS

Synchronous condensers are synchronous machines running without a prime mover or mechanical input load. The generators at Umtata 1st and 2nd falls in Transkei can be operated as synchronous condensers. By controlling the field excitation, it can be made to either generate or absorb reactive power. With a voltage regulator, it can automatically adjust the reactive power output to maintain constant terminal voltage. It draws a small amount of active power from the power system to supply losses. Synchronous generators are further discussed in sub-section 8.4.1. [31]

STATIC VAR COMPENSATORS

Static var compensators (SVCs) are shunt-connected static generators and/or absorbers whose outputs are varied so as to control specific parameters pf the electric power system. SVCs do not have moving or rotating components like synchronous condensers. There are a number of different types of static var compensators, these include [31];

- Saturated reactor (SR)
- Thyristor controlled reactor (TCR)
- Thyristor-switched capacitor (TSC)
- Thyristor switched reactor (TSR)
- Thyristor controlled transformer (TCT)
- Self or line commutated converter (SCC/LCC)

On distribution networks SVCs are used for balancing the three phases of systems supplying unbalanced loads, as well as minimising fluctuations in supply voltage caused by repetitive impact loads such as arc furnaces and rolling mills. The purpose of the Zimbane SVC is to provide reactive power compensation when required.

8.3.3 DYNAMIC BRAKING

Dynamic braking reduces accelerating torques of generators by applying an artificial load during a transient disturbance. One type of dynamic braking resistor is the switching in of shunt resistors for about 0.5seconds following a fault to reduce the accelerating power of nearby generators and remove the kinetic energy gained during the fault. According to Kundur [31], braking resistors are applied to hydro generating stations remote from load centres. Hydro plants are quite rugged and can withstand the sudden shock from the switching in of resistors without adverse effects on the units.

8.3.4 HIGH-SPEED EXCITATION SYSTEMS

Transient stability can also be improved through the rapid temporary increase of generator excitation. The increase of generator field voltage during a transient disturbance has the effect of increasing the internal voltage of the machine, this in turn increases the synchronising power. After the occurrence of a severe transient disturbance the generator field voltage is low. The AVR responds by to this condition by increasing the field voltage, and this is beneficial to transient stability. The effectiveness of this type of control depends on the ability of the excitation system to quickly increase the field voltage to the highest possible value. However fast excitation response to terminal voltage variations for the improvement of transient stability usually leads to degrading the damping of local plant mode oscillations. Usually power system stabilisers (PSS) are used to improve the damping of system oscillations after the use of high response excitation systems. [31]

This operation might be expensive for typical distributed generators that are connected to the distribution network, because of the additional power system stabiliser that would have to be connected. However if a very fast excitation system that does not affect the damping of local plant mode can be designed, it would be beneficial because it would be economical and also improve stability.

8.4 IMPROVING VOLTAGE STABILITY AND PREVENTION OF VOLTAGE COLLAPSE

Voltage stability can be improved by mainly maintaining a reactive power balance in a distribution network. Some of the system design measures include application of reactive power-compensating devices and control of network voltage and generator reactive power output. The majority of these methods inject reactive power into the network and compensate the inadequate amount that exists in the system. This section presents the different methods of improving voltage stability and prevention of voltage collapse.

8.4.1 REACTIVE POWER COMPENSATING DEVICES

There are a wide variety of reactive power compensating devices that can be used. These include static as well as dynamic (rotating) devices. However adequate stability margins should be ensured by the proper selection of compensating schemes. Some of the compensating devices that will be looked at in this section include shunt capacitors, static var systems, synchronous condenser and series capacitors.

Shunt capacitors

The utilisation of shunt capacitors is one of the cheapest methods of providing reactive power reserves and voltage support at the end of distribution networks. Shunt capacitors however have a number of inherent limitations from a voltage stability and control point of view. According to Shikoana [49], shunt capacitors can be used to prevent voltage instability even though beyond a certain level of compensation stable operation is unattainable with shunt capacitors. However even though shunt capacitors have this limitation they are still one of the most viable options, especially where a high penetration of induction generators are connected because of the their cost.

Series capacitors

The reactive power supplied by series capacitors is proportional to the square of the line current and does not depend on voltages. This is therefore beneficial from a voltage stability point of view, because when the voltage progressively decreases the reactive power does not decrease with it. Series capacitors improve both voltage regulation and stability since they reduces both the characteristic impedance and the electrical length of the line. [37]

For voltage stability, series capacitors lower the critical or collapse voltage, and they have a significant time over-load capability. The cost of installing series capacitors on a distribution network is not an expensive exercise. It is also one of the most viable options because of its reduced installation cost. However the disadvantages of series capacitors are the fact that they are line connected, compensation is removed for outages and capacitors in parallel lines may be overloaded. Also during heavy loading (outages of parallel lines), the voltage on one side of the series capacitor may be out of range. [51]

Static var systems

Static var systems regulate up to its maximum capacitive output. There is no voltage control or instability problem within the regulating range. When the limit is reached, the SVS becomes a capacitor. They can also attempt to control the voltages on bus bars when unstable induction generators start demanding large amounts of reactive power. In this manner they improve the voltage stability on distribution networks.

Synchronous condensers

Synchronous condenser supply reactive power to relatively low voltages and contribute to a stable voltage performance. The advantages that synchronous condensers have over static compensators include [31];

- Their reactive power is not affected by the system voltage changes
- During power swings there is an exchange of kinetic energy between a synchronous condenser and the power system. And during the power swings the condenser can supply approximately double the amount of reactive power
- It has an internal voltage source and is better able to cope with low voltage conditions

According to Taylor [51], synchronous condensers (SCO) have advantages over SVCs in voltage weak networks. Following a drop in network voltage, the increase in condenser reactive power output is instantaneous (same for generator reactive power output). The subsequent decay of internal voltage or flux is countered by excitation control. In contrast to the voltage squared capacitor characteristic of SVCs at full boost, condensers can maintain rated current at full boost due to their overload capability. SVCs are however preferred due to the fact that they strictly used for reactive power compensation. Whereas SCOs are not always available to be used as reactive power compensators because the rotating machine is used as a generator as well as a SCO.

8.4.2 CONTROL OF REACTIVE POWER SUPPLY

A generator AVR regulates voltage on the bus to which it is connected, and by so doing contributes to load compensation. In many situations this has a beneficial effect on voltage stability by moving the point of constant voltage electrically closer to the loads. Synchronous generators have the added advantage of controlling the amount of reactive power they can contribute to the network, where as induction generators only draw reactive power from the network.

8.4.3 COORDINATION OF PROTECTION/CONTROLS

One of the causes of voltage collapse is the lack of coordination between equipment protection/controls and power system requirements. Sufficient coordination should be ensured based on dynamic simulation studies. If the protection fault clearing times are set to be less than the critical fault clearing times of the distributed generators, the generators would not lose their stability and degrade the quality of supply of a particular distribution network.

8.5 RECOMMENDATIONS FOR THE TRANSKEI NETWORK

When this thesis was almost completed, the Transkei network experienced several voltage slides that resulted in cascading trips of most of the hydro power stations. The voltage slides occurred during peak load hours. The occurrence of events that resulted in the voltage slides was as follows;

- Three phase faults occur on the Umtata city area, that take up to 1.2 seconds to clear. This depresses the voltage on the 132kV bus to 70KV, and drops the contactors on the cooling water pumps (SVC) which then results in a SVC trip.

- Second falls trips instantly due to the fact that the station is operated automatically on power factor mode.
- Each Mbashe machine then trips at approximately 45 second intervals.
- First falls with its old AVR rides through the event possibly adjusting to zero power output.

It is therefore evident that the Transkei network is reliant on the SVC at Zimbane for reactive power compensation, especially during peak hours. Hence without the SVC, the Transkei network is likely to experience voltage stability problems during peak hours. This is because during peak hours, all the hydro power stations are used as peak lopping stations and the generators at Umtata are not able to operate as synchronous condensers. It is also evident that the Transkei network has transient stability problems, especially after the occurrence of transient disturbances on the network.

From the visit that was also made to the hydro power stations in Transkei it was evident that the reliability of the generators after the occurrence of large disturbances on the system was not satisfactory. The Transkei network therefore has transient stability problems, due to the fact that protection on the system is not able to clear the faults before the critical fault clearing time of the hydro generators.

Hence the following stability recommendations are proposed;

- Coordination between equipment protection/controls and power system requirements should be reviewed. The protection fault clearing times have to be set so that they clear faults before the critical fault clearing times of the hydro generators. The system has enough sources of reactive power compensation, which include synchronous condensers, capacitor banks and static var compensators. Hence coordination of these sources would improve the stability problem.
- High speed excitation systems at the hydro power stations would be effective in increasing the critical fault clearing times of the generators.
- High speed fault clearing would be the solution to many problems.

8.6 SUMMARY

The implications of potential instability caused by the connection of distributed generators onto distribution networks were discussed. Instability of distributed generators was seen to mainly violate power quality standards set out by the South African NRS 048 standard [45]. Methods of improving stability on distribution networks that would reduce the impact of potential stability were also presented.

The implications of potential stability were separated into the two forms of instability that are likely to occur on a distribution network once a distributed generator is connected, and these forms of instability include transient instability and voltage instability. The main cause of these instabilities was discovered and simulated to being large disturbances. A severe large disturbance on a distribution network that causes a synchronous generator to lose its stability was found to result in the generator pole slipping and losing synchronism with the distribution network. The pole slipping leads to fluctuations in the networks voltage. This would greatly impact the quality of supply on the distribution network. The fluctuation in network voltage would occur if the unstable generator is not disconnected from the network. A simulation done in Case study 1 verified these implications.

The major cause of voltage instability is the connection of induction generators. The drawing of large amounts of reactive power by induction generators during the occurrence of a large disturbance was found to be the main contributing factor. This property of the induction generator resulted in a drop in network voltage or a progressive fall in voltage depending on the strength of the network as well as the penetration of induction generators. However if the induction generator is disconnected once it loses stability and starts drawing large amounts of reactive power, the network voltage recovers.

Extremely weak distribution networks that require distributed generation for voltage support were realised to easily lose stability after the occurrence of a transient disturbance. This is because the disturbance results in the generator losing its stability and being disconnected, and this greatly affects the network that relies on the distributed generator for voltage support. The stability of extremely weak distribution networks that utilise DG for voltage support is hence likely to be poor.

Several methods of improving the transient and voltage stability of a network were discussed, however the most important methods included reactive power compensation, high speed excitation systems and coordination of protection/controls.

CHAPTER 9

CONCLUSIONS

When distributed generation is connected to distribution networks it is likely to degrade the stability of the connected distribution network unless fast protection is utilised to prevent the distributed generators from losing stability. Under normal steady state conditions distributed generation is likely to improve the overall performance of the distribution network it is connected to, depending on the type of distributed generation technology used. Even though distributed generators strengthen the distribution networks they were connected to, after the occurrence of large nearby disturbances they were susceptible to losing stability. The strength of the network they are connected to plays an important role in determining the stability of the distribution network.

This chapter contains five sections. The first section draws conclusions on the impact of distributed generation technologies on distribution network stability, based on the review of previous work as well as the chapter 3 and 4. The second section draws conclusions on the results of the stability studies that were conducted, based on chapter 5, 6 and 7. The next section draws conclusions on the implication of potential instability on distribution networks. The fourth section reviews the validity of the hypothesis stated in the chapter 1. The last section considers the scope for future work that can be done as a result of the work covered in this thesis.

9.1 DISTRIBUTED GENERATION

The conclusions regarding the impact of distributed generation technologies on distribution network stability are listed below:

- The main forms of stability that are of concern when distribution networks are connected with distributed generators include transient stability and voltage stability. The literature review revealed that small signal stability does not greatly impact the stability of distribution networks connected with DG, however this impact must not be over looked. Small signal stability is hence a possible area of study that can be focused on in future study.

- Hydro generators, wind generators and photovoltaic generators were identified as the type of generators that are likely to be connected to the Southern African distribution networks due to the resources that are located in the region.
- Even though there are many different types of distributed generation technologies, they can be grouped into three categories. These categories include synchronous generator based technologies, induction generator based technologies and power electronic based technologies. Within each category the difference between the generators would be the type of prime mover that is utilised by the distributed generation technology. After focusing on the type of electrical machinery utilised by the generator rather than the type of DG technology, the results of the stability studies can also apply to other DG technologies that utilise similar electrical machinery.
- Distribution networks that are connected with distributed generators that utilise synchronous machines were found to be susceptible to transient instability. After the occurrence of nearby large disturbances, the distributed generators were likely to lose synchronism with the network they are connected to, by pole slipping.
- Distribution networks that are connected with distributed generators that utilise asynchronous generators were found to be susceptible to voltage instability. After the occurrence of nearby large disturbances the distributed generators were likely to draw large amounts of reactive power, which can lead to the voltage collapse of the distribution network.

9.2 RESULTS FROM STABILITY STUDIES CONDUCTED

The conclusions drawn from the stability studies conducted are listed below:

- Large disturbances were identified as being the biggest threat to the voltage stability as well as the transient stability on distribution networks, especially on electrically weak distribution networks.
- The fault location when carrying out stability studies proved to be a big determining factor of stability. It was demonstrated that the closer a large disturbance is to a synchronous generator the shorter the critical fault clearing time (CCT), and the further away the large disturbance is from the synchronous generator the longer the CCT. This result demonstrated that the most severe fault that would greatly affect the transient stability is a fault close to the distributed generator. Fast fault protection that would be able to clear all types of short circuit faults that occur on the terminals of the generator would be recommended to try to prevent the generator from reaching its stability limit.

- Distributed generator loading was found to be another factor that greatly affects the transient stability as well as the voltage stability of a distribution network. When a distributed generator is heavily loaded it quickly reaches its stability limit, and when it is lightly loaded it takes more time to reach its stability limit.
- It was shown that the electrical parameters of distributed generators greatly contribute to the transient stability of the generators. The transient reactance (Xd') as well as the inertia constant (H) were found to have the most significant effect on the critical fault clearing time (CCT) of the synchronous generator. It was established that the higher the inertia constant the longer the CCT, and the lower the inertia constant the shorter the CCT. Small generators are characterised with small inertia constants (H), and as generating capacity size increases the inertia constants also increase. This therefore implied that smaller generators had a poorer transient stability as compared to larger generators. On the other hand, it was established that the smaller the transient reactance (Xd') the longer the critical fault clearing time (CCT), and the larger the transient reactance (Xd') the shorter the CCT. The transient reactance of generators was identified to be influenced by the design of the distributed generator. Therefore it would be ideal to have distributed generators that have smaller values of Xd' in order to improve the transient stability of the generators. Distributed generators that would be connected to distribution networks would hence be designed to have the smallest possible value of transient reactance and the largest possible value of inertia constant. The practical implication of this design would result in generators having large diameters (in order to increase the inertia) and shorter lengths (in order to reduce transient reactance value), which could possibly be designed to improve the stability of DGs.
- Induction generators were discovered to significantly contribute to voltage instability, mainly because after the occurrence of a large disturbance the reactive power demand of the generator is high. Just like synchronous generators, induction generators showed that when the power production was increased the generator quickly reached its stability limit in the event of a fault.
- Electrically weak distribution networks that are connected with DG were found to be susceptible to DG instability. When a distributed generator lost its stability on a weak network, depending on the size of the distributed generator, the voltage profiles as well as the power flows were greatly distorted. The effects of the electrically weak network resulted in the voltage stability problem, caused by the high reactive power demand of the induction generators, becoming worse.
- The Governor controller was found not to significantly improve the critical fault clearing time (CCT) of a synchronous machine based distributed generator. The governor however was found to limit the over speeding of the generator and reduce the input mechanical power after the generator loses its stability.

9.3 IMPLICATION OF POTENTIAL INSTABILITY

The conclusions drawn on the implications of potential instability on the distribution network are listed below:

- The implication of transient instability on a distribution network that is connected with synchronous generators were dramatic fluctuation of the generator's currents and as a result caused fluctuations in the distribution networks' voltage. The implication of voltage instability on a distribution network that is connected with induction generators were a progressive fall or rise of voltages on the bus bars. These instabilities would be undesirable to the consumer.
- Methods of improving stability on distribution networks connected with distributed generation were identified. Some of these methods are not implemented due to the high cost of implementation. However, the important methods include reactive power compensation, high speed excitation systems and coordination of protection/controls.

9.4 REVIEW OF HYPOTHESIS

The hypothesis that guided this research stated, " Distributed generation that is connected to a weak distribution network will not degrade the system stability, but instead improves the general stability of the local distribution network because it increases the strength of the network."

The findings of this thesis show that distributed generators can degrade the stability of distribution networks if they are not disconnected quickly when faults occur. If the generators are disconnected quickly the power quality on the local distribution is not made worse. The effect of distributed generators being connected to weak systems worsens the stability problem because instability on the system is not only contributed by the generator, but is also contributed by the weak distribution network. It has been realised that:

- unstable distributed generators that utilise synchronous generators cause dramatic fluctuation of the generator's currents that cause fluctuations in the distribution networks' voltage.
- unstable distributed generators that utilise induction generators draw large amounts of reactive power which lowers the distribution network voltage or even results in a voltage collapse.

It is therefore clear that one of the most significant factors that determine the extent to which the stability of the distribution network is affected, is the type and size of the distributed generator as well as the strength of the distribution network. It is therefore important to ensure that fast protection is used to clear faults before the distributed generators reach their critical stability limits.

Another important finding of this thesis is that if a distribution network is electrically weak and requires distributed generation to support the network, for example connecting distributed generation at the end of a long distribution line, the distributed generator will definitely lose its stability when a large disturbance is introduced on the network. This is because the network is not strong enough to support itself. Due to the fact that some distributed generators have independent control of real and reactive power, they are able to strengthen some weak networks especially in steady state conditions however once severe large disturbances are introduced onto the network the generator contributes to the fault and it is unable to strengthen the network.

9.5 SCOPE FOR FUTURE WORK

The Stability issues of distribution networks that are connected with distributed generation have been highlighted by this thesis. It was the objective of this thesis to investigate the general stability issues that are raised when distribution networks are connected with DG. However because different networks are uniquely designed and are different, in order to carry out a stability study of a particular network it is important to fully model it. Further work on particular networks can hence be done on specific networks that are connected to DG. For example, instead of carrying out a study where one or two wind generators are connected to a distribution network, stability studies of a wind farm with a lot more wind generators can be conducted. This is because a detailed stability for a specific network is more useful, because from the stability study protection times can be set and suitable methods of improving stability can be recommended.

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APPENDICES

Appendix A: Electrical data for Case Study 1 & Simulation Results

Appendix B: Electrical data for Case Study 2 & Simulation Results

Appendix C: Electrical data for Chapter 7 & Simulation Results

Appendix D: Electrical data for Case Study 3 & Simulation Results

Appendix E: Electrical data for Case Study 4 & Simulation Results

Appendix F: Transkei sample photographs

Appendix G: AVR & Governor models

Appendix H: ACSR Physical and Electrical data

APPENDIX A

ELECTRICAL DATA FOR CASE STUDY 1 & SIMULATION RESULTS

Synchronous Generator

Rated Voltage	7.967kV
Rated MW	5MW
Power factor	0.9
Connection	YN
Stator resistance [r_s]	0.051716
Leakage Reactance [X_l]	0.0163
Xd	2.062
Xq	1.35
X'd	0.251
X'q	0.63
X"d	0.171
X"q	0.171
Td'	0.670712
T'q	0.373333
T"d	0.0681275
T"q	0.02714286

Governor (synchronous machine)

Tw	1
Qnl	0
Tg	0.2
Actual turbine power coeff [At]	1
Turbine nominal power [Pturb]	0
Dturb	0
R	0.04
Tf	0.01
Tr	0.05
Gmin	0
Gmax	1
Velm	0.16

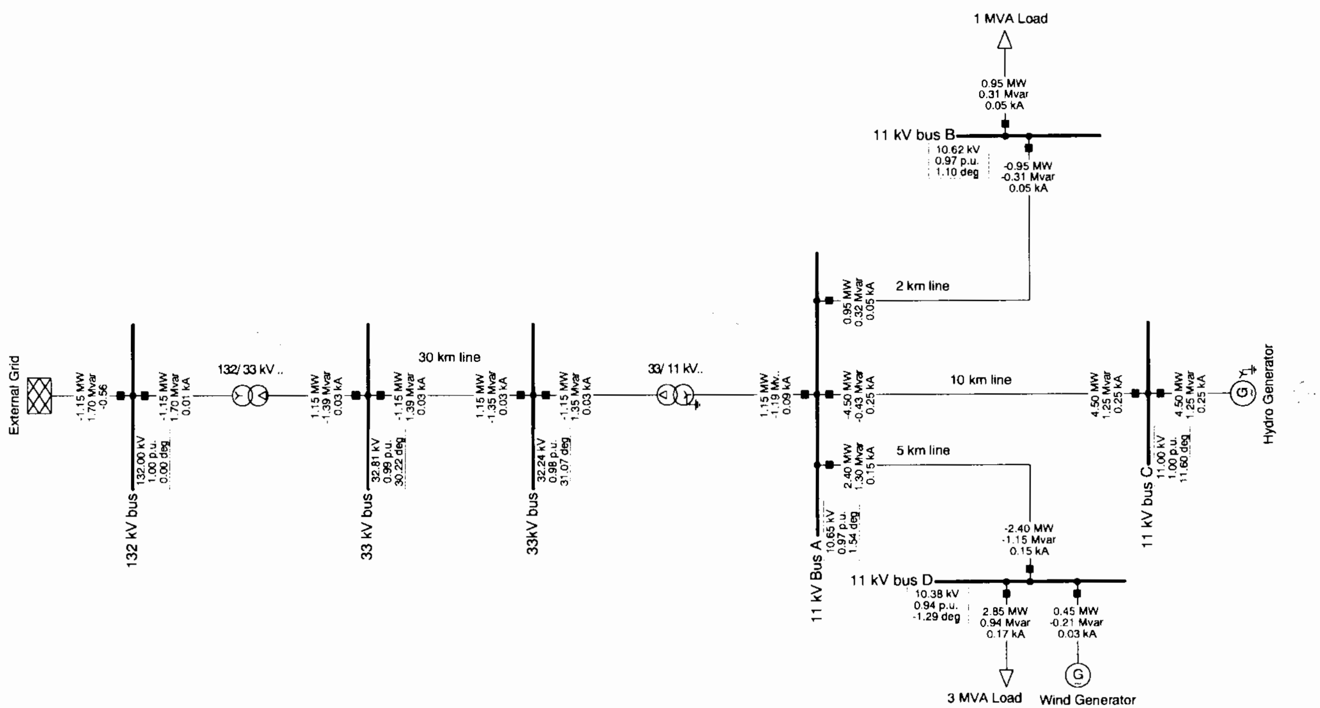
Exciter (synchronus generator)

Tr	0
Kc	0.2
Tb	0
Tc	0
Ka	400

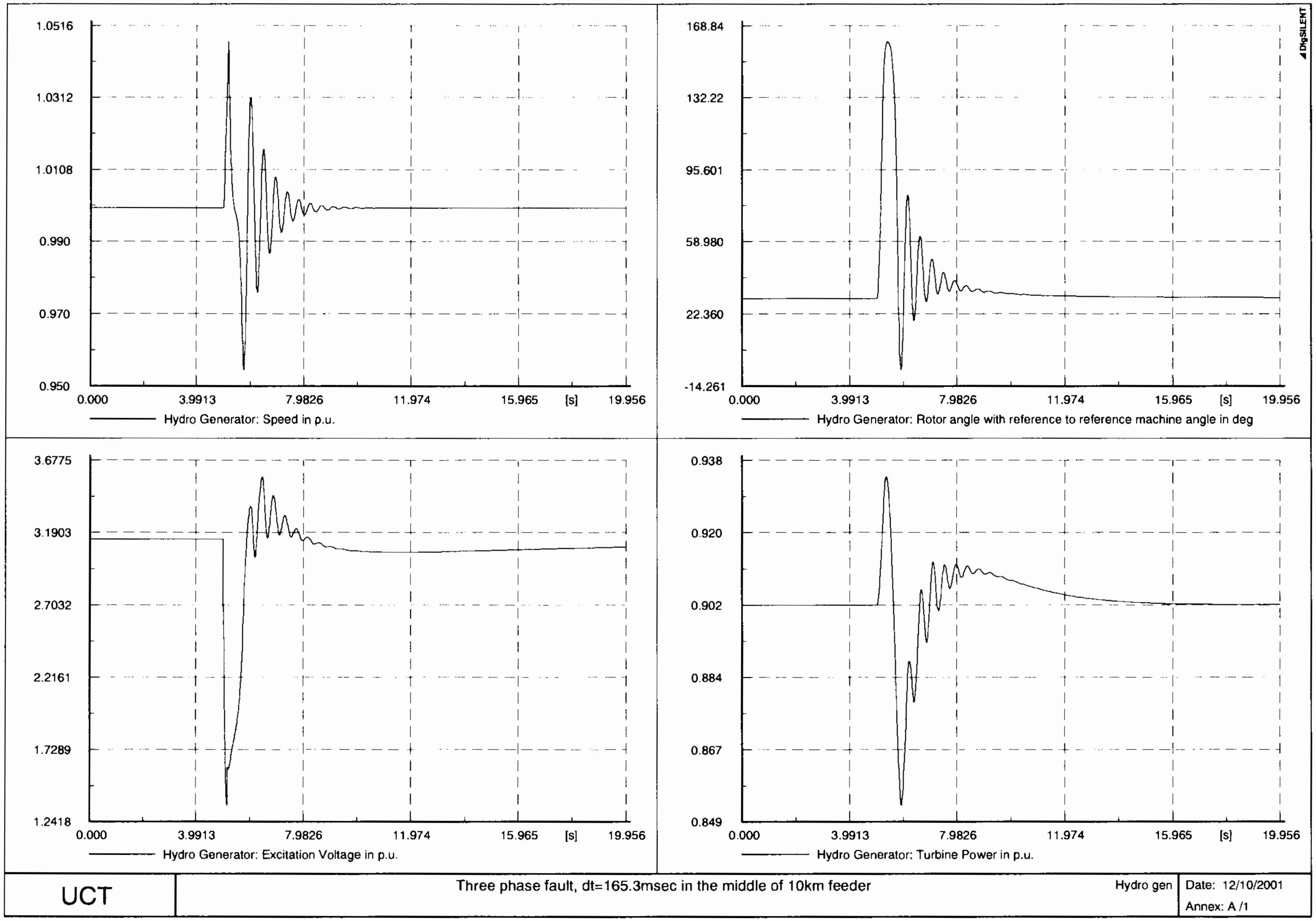
Ta	0.02
Te	0.8
Ke	1
E1	4.18
SE1	0.1
E2	0.03
SE2	3.14
Kd	0.38
Kf	0.03
Tf	1
Vrmin	-5.43
Vrmax	6.03

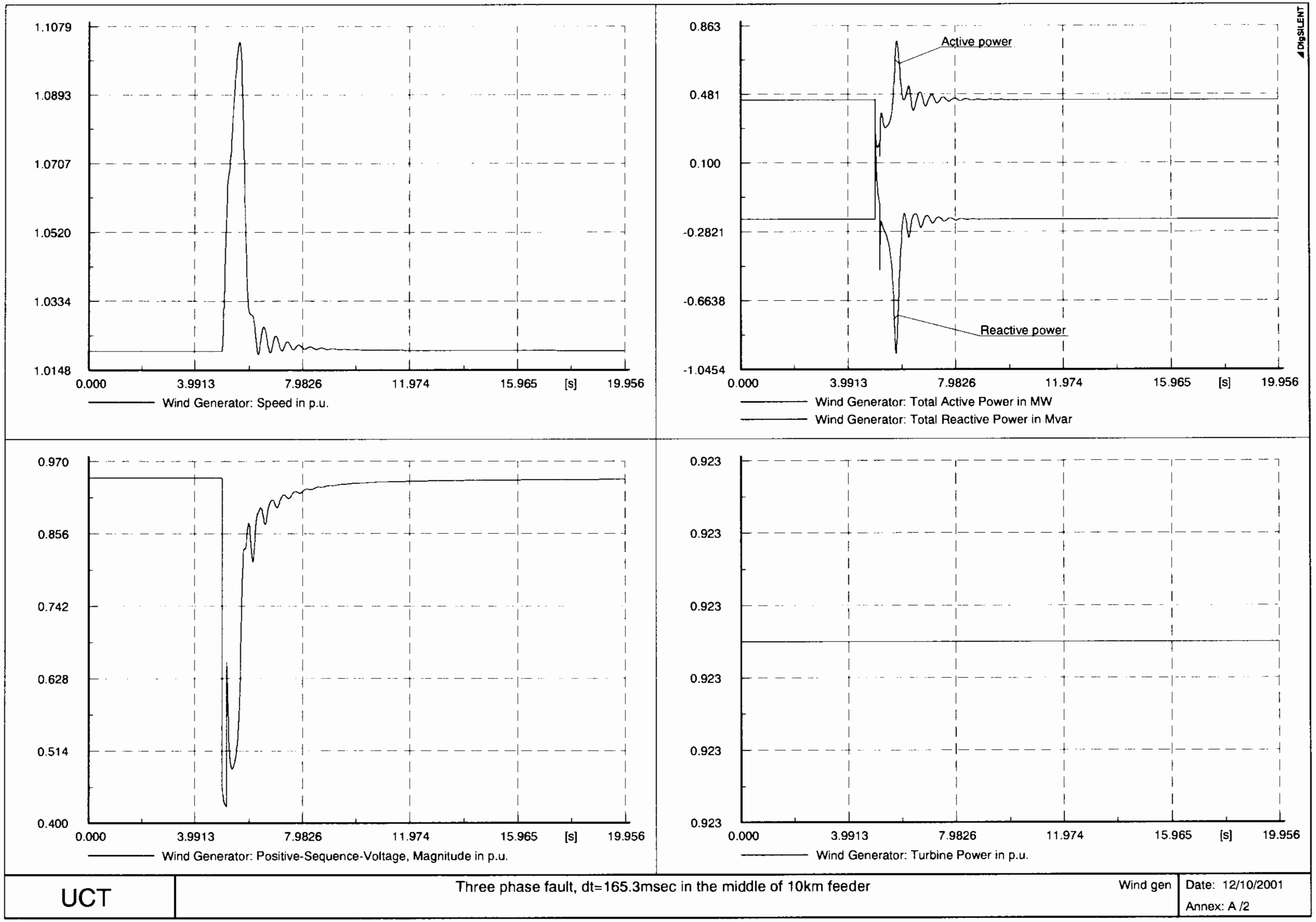
Induction Generator

Rated Voltage	11kV
Rated MW	0.5MW
No of pole pairs	1
Connection	D
Rotor	Single Cage
Stator resistance [Rs]	0.0054
Mag. Reactance [Xm]	4.34 p.u.
Stator Reactance [Xs]	0.0852 p.u.
Rotor Resistance [R_{rA}]	0.0206 p.u.
Rotor Reactance [X_{rA}]	0.139 p.u.
Acc. Time constant	2 secs

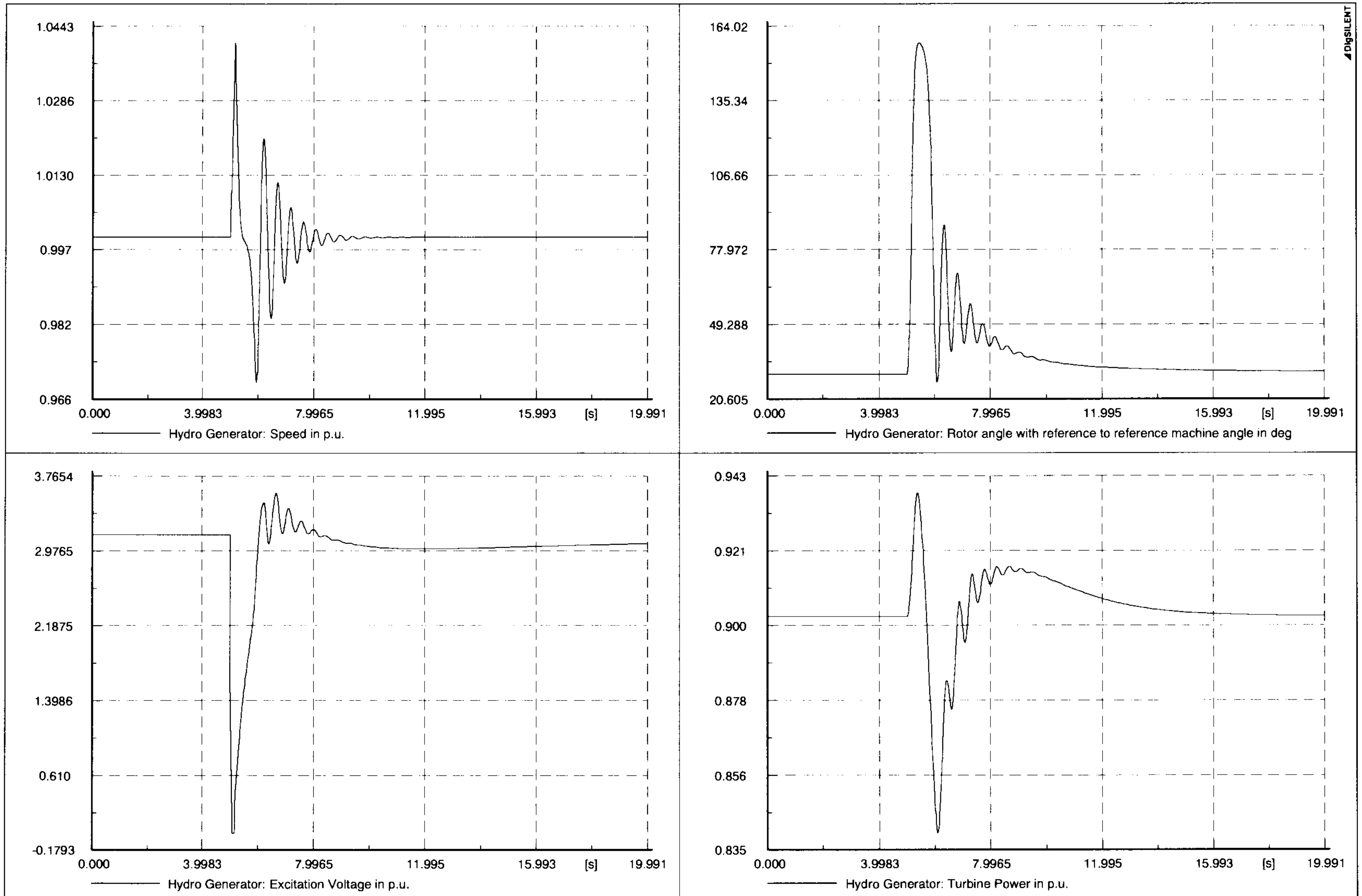


DIgSILENT	Stability of Distributed Generation	Project: UCT
	Case Study 1 Typical Southern African Distribution network	Graphic: Network 1
		Date: 12/10/2001
PowerFactory 12.1.166		Annex: A

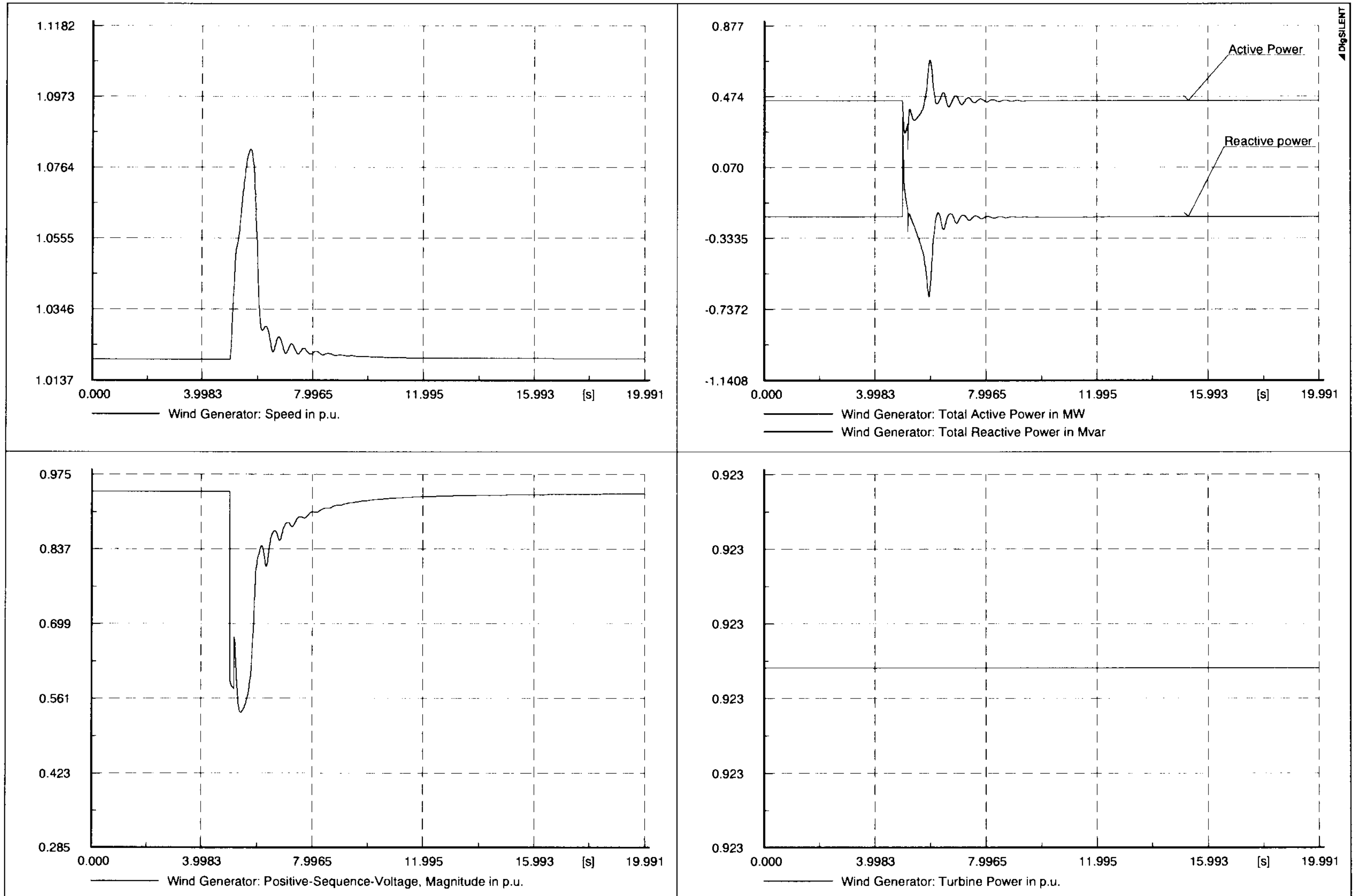

1.0516
1.0312
1.0108
0.990
0.970
0.950
0.000
3.9913
7.9826
11.974
15.965
[s]
19.956
Hydro Generator: Speed in p.u.
168.84
132.22
95.601
58.980
22.360
-14.261
0.000
3.9913
7.9826
11.974
15.965
[s]
19.956
Hydro Generator: Rotor angle with reference to reference machine angle in deg
DIgSILENT
3.6775
3.1903
2.7032
2.2161
1.7289
1.2418
0.000
3.9913
7.9826
11.974
15.965
[s]
19.956
Hydro Generator: Excitation Voltage in p.u.
0.938
0.920
0.902
0.884
0.867
0.849
0.000
3.9913
7.9826
11.974
15.965
[s]
19.956
Hydro Generator: Turbine Power in p.u.
UCT
Three phase fault, dt=165.3msec in the middle of 10km feeder
Hydro gen
Date: 12/10/2001
Annex: A /1



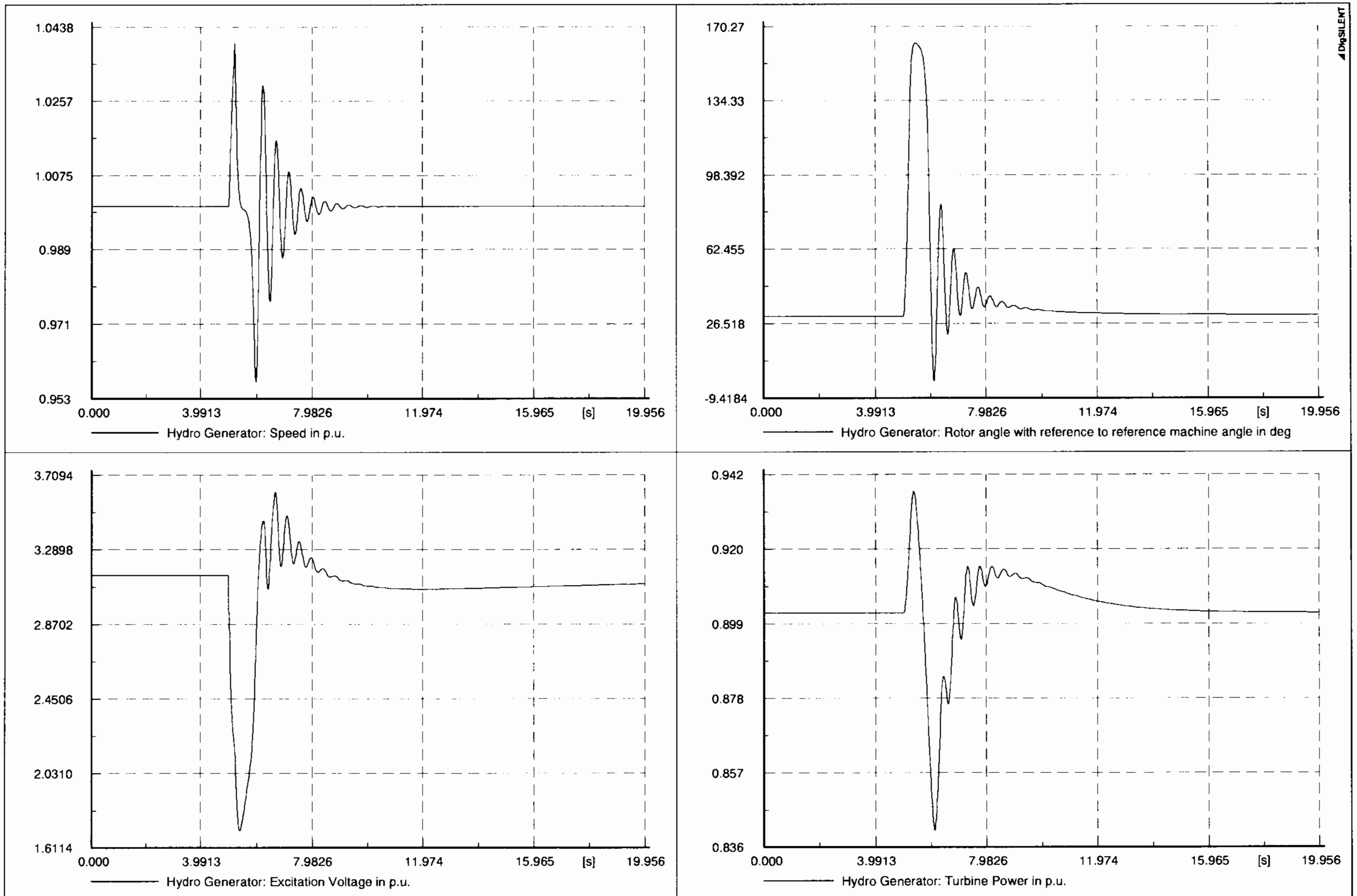
1.1079
1.0893
1.0707
1.0520
1.0334
1.0148
0.000
3.9913
7.9826
11.974
15.965
[s]
19.956
Wind Generator: Speed in p.u.
0.863
0.481
0.100
-0.2821
-0.6638
-1.0454
Active power
Reactive power
Wind Generator: Total Active Power in MW
Wind Generator: Total Reactive Power in Mvar
DIgSILENT
0.970
0.856
0.742
0.628
0.514
0.400
Wind Generator: Positive-Sequence-Voltage, Magnitude in p.u.
0.923
Wind Generator: Turbine Power in p.u.
UCT
Three phase fault, dt=165.3msec in the middle of 10km feeder
Wind gen
Date: 12/10/2001
Annex: A /2



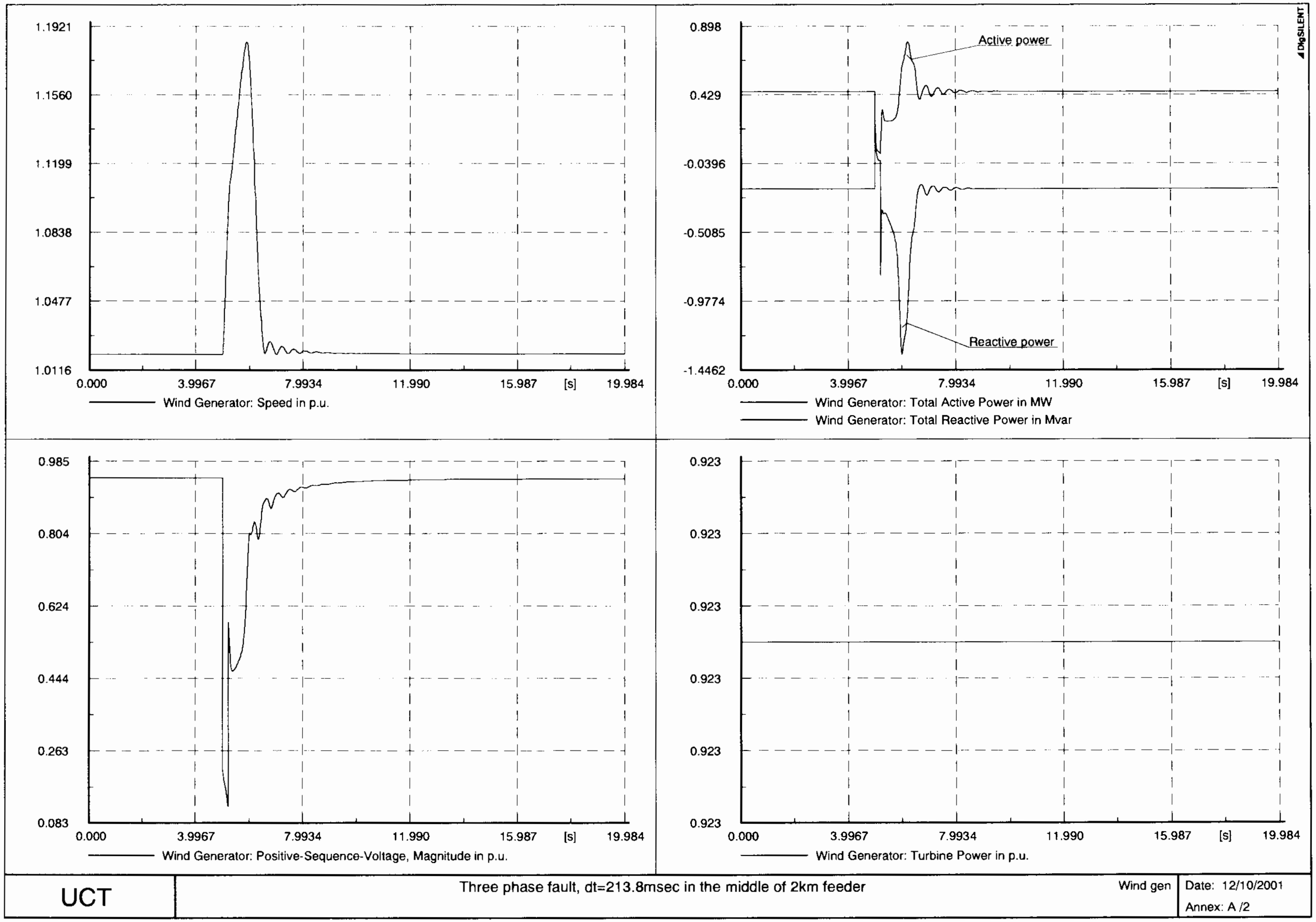
UCT	Three phase fault, dt=178.2msec on terminals of hydro generator	Hydro gen	Date: 12/10/2001 Annex: A /1

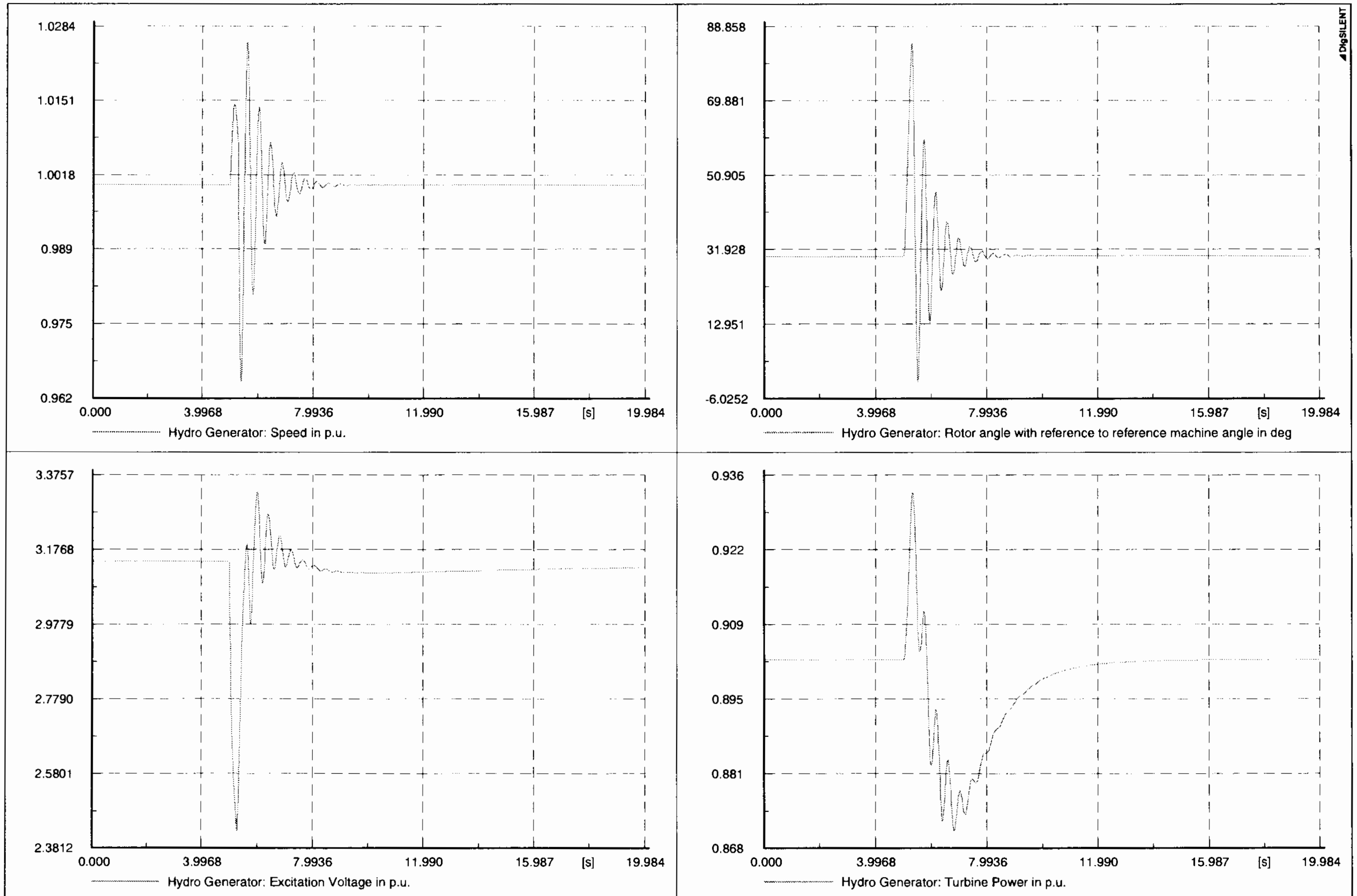


UCT	Three phase fault, dt=178.2msec on terminals of hydro generator	Wind gen	Date: 12/10/2001 Annex: A /2

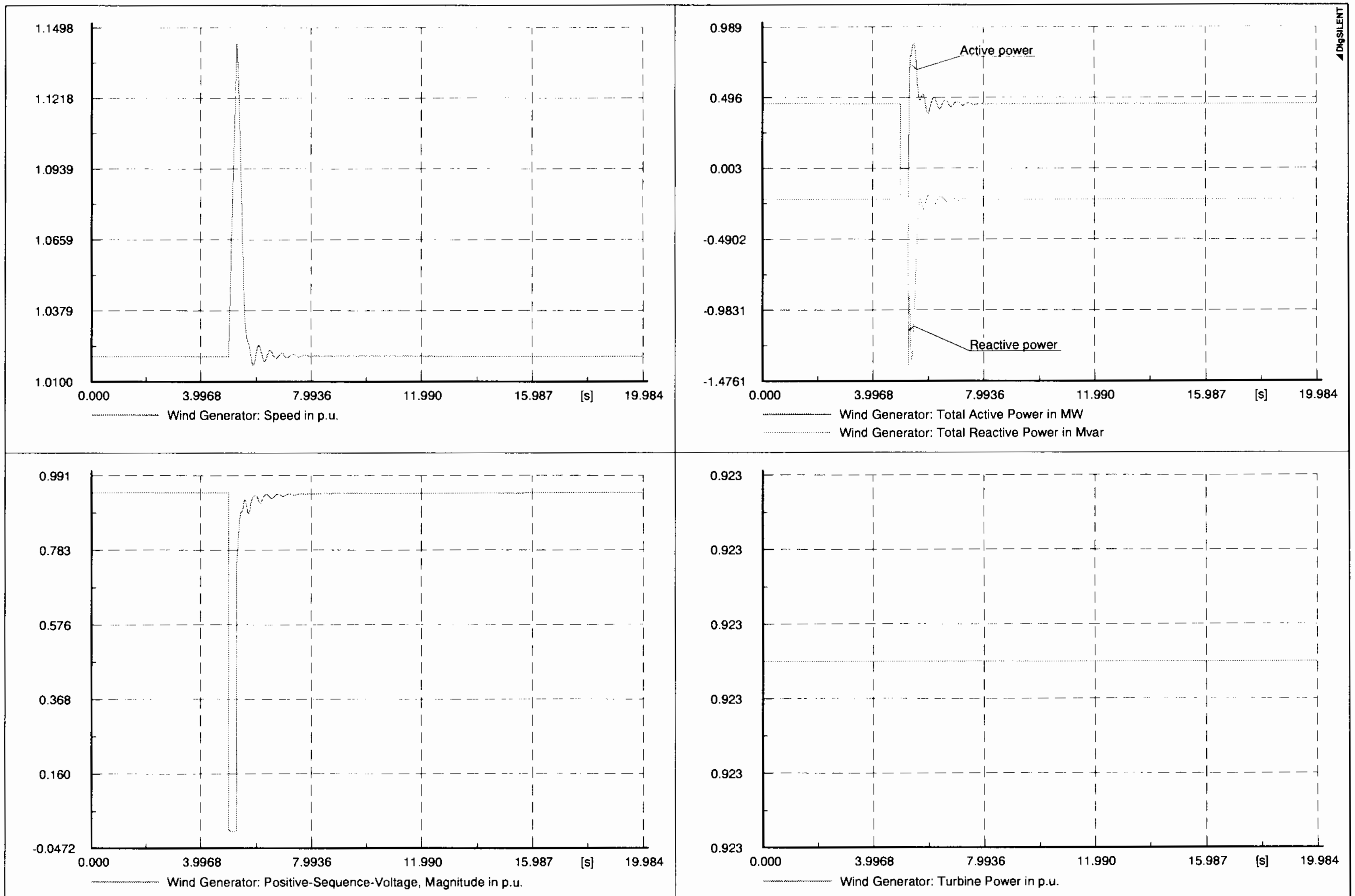


UCT	Three phase fault, dt=213.8msec in the middle of 2km feeder	Hydro gen	Date: 12/10/2001 Annex: A /1

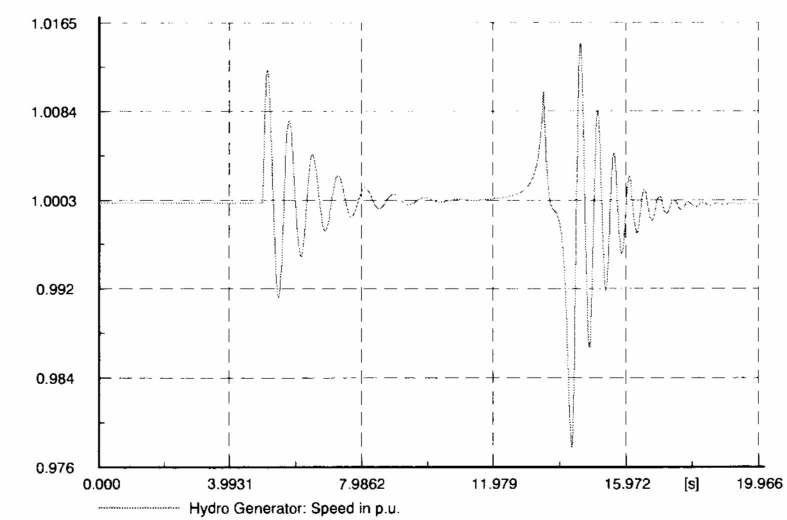

1.1921
1.1560
1.1199
1.0838
1.0477
1.0116
0.000
3.9967
7.9934
11.990
15.987
[s]
19.984
Wind Generator: Speed in p.u.
0.898
0.429
-0.0396
-0.5085
-0.9774
-1.4462
Active power
Reactive power
Wind Generator: Total Active Power in MW
Wind Generator: Total Reactive Power in Mvar
DIgSILENT
0.985
0.804
0.624
0.444
0.263
0.083
Wind Generator: Positive-Sequence-Voltage, Magnitude in p.u.
0.923
Wind Generator: Turbine Power in p.u.
UCT
Three phase fault, dt=213.8msec in the middle of 2km feeder
Wind gen
Date: 12/10/2001
Annex: A /2

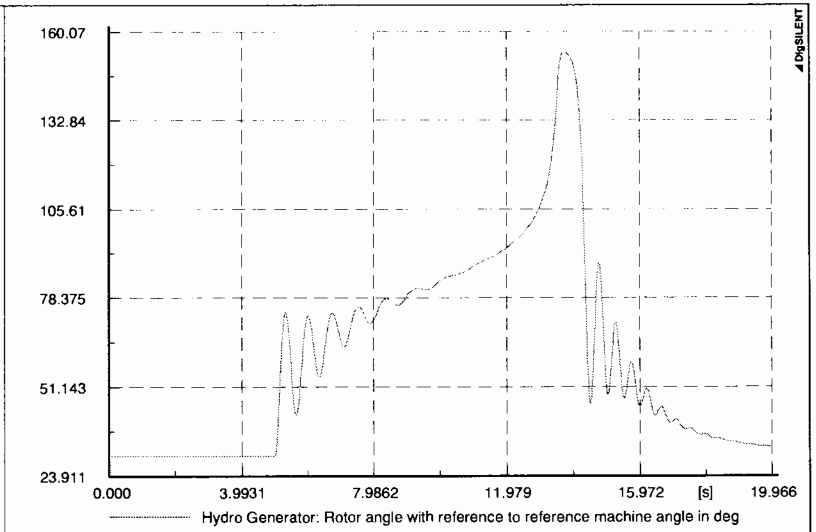


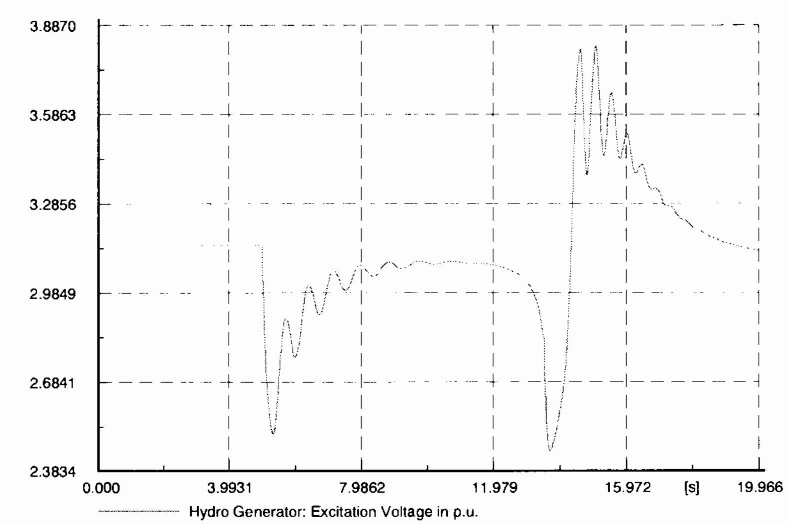
UCT	Three phase fault, dt=2795.5msec 4km away from 11kV bus A on the 5km feeder	Hydro gen	Date: 12/10/2001 Annex: A /1

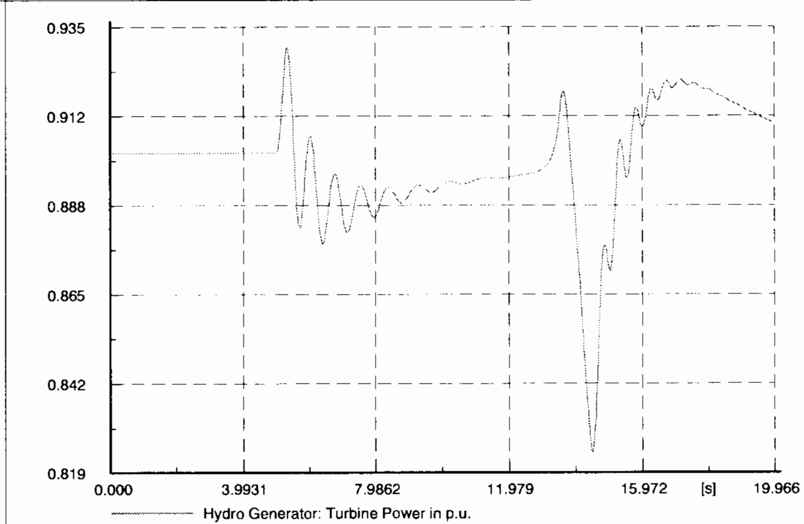


UCT	Three phase fault, dt=2795.5msec 4km away from 11kV bus A on the 5km feeder	Wind gen	Date: 12/10/2001 Annex: A /2

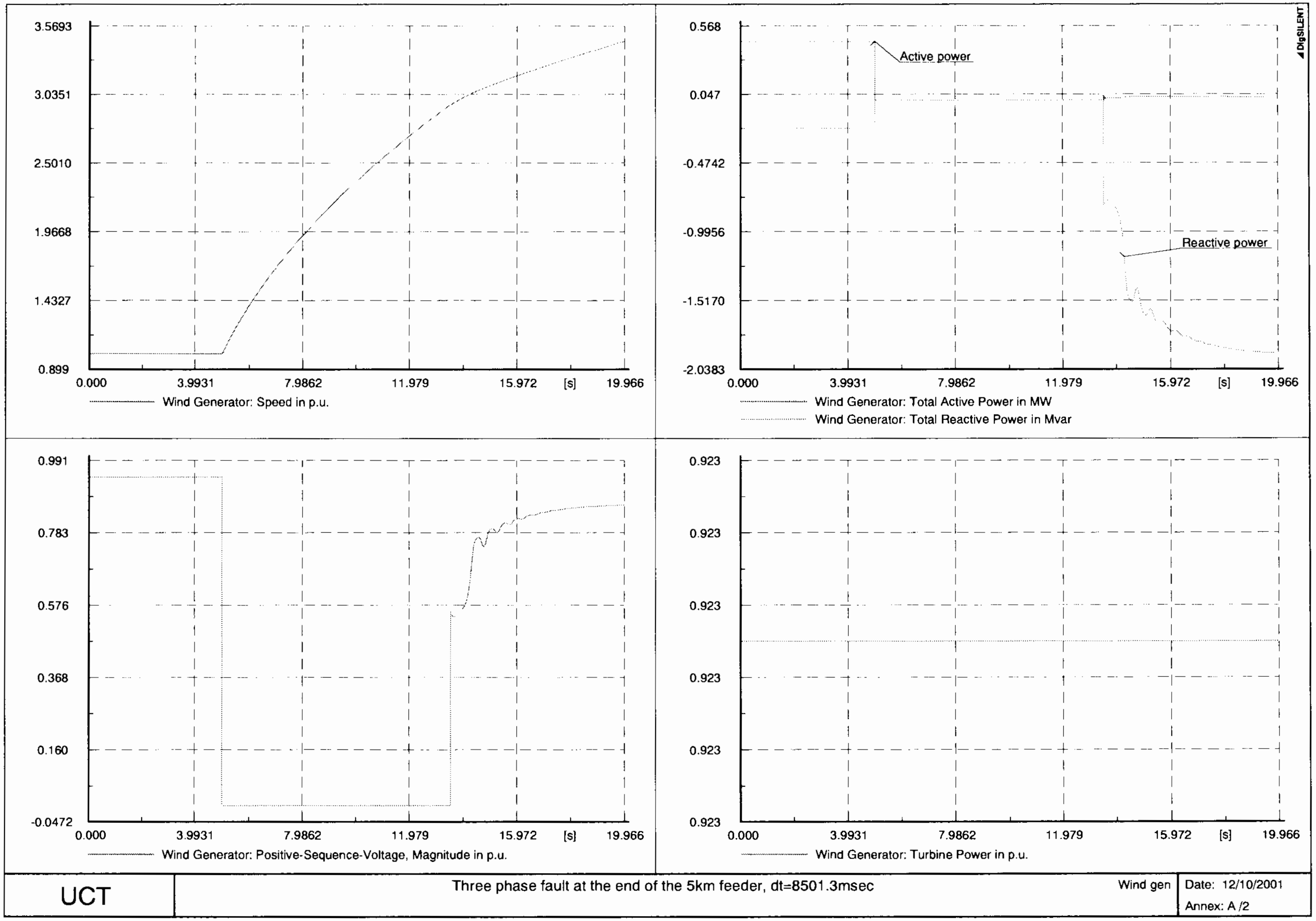


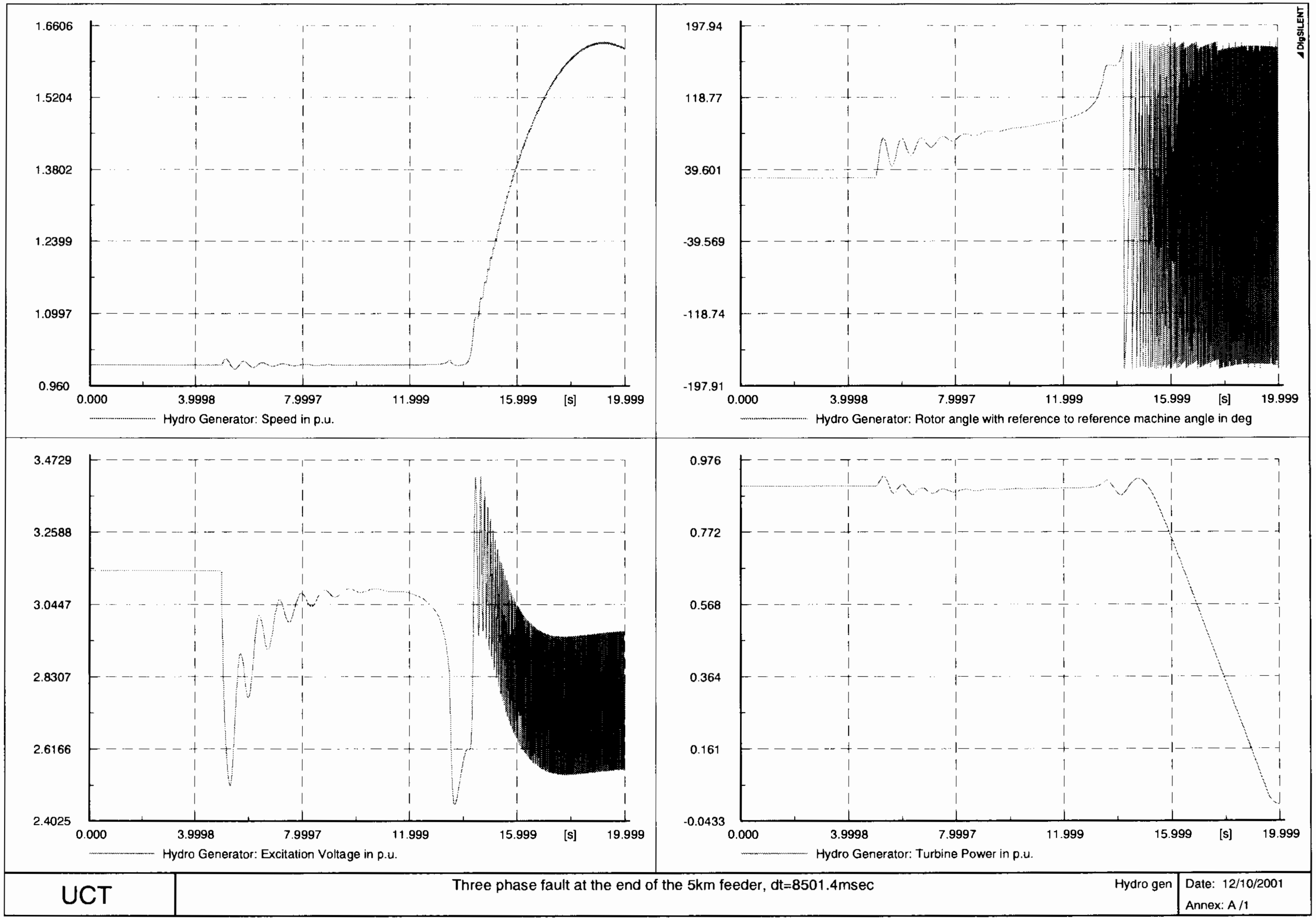


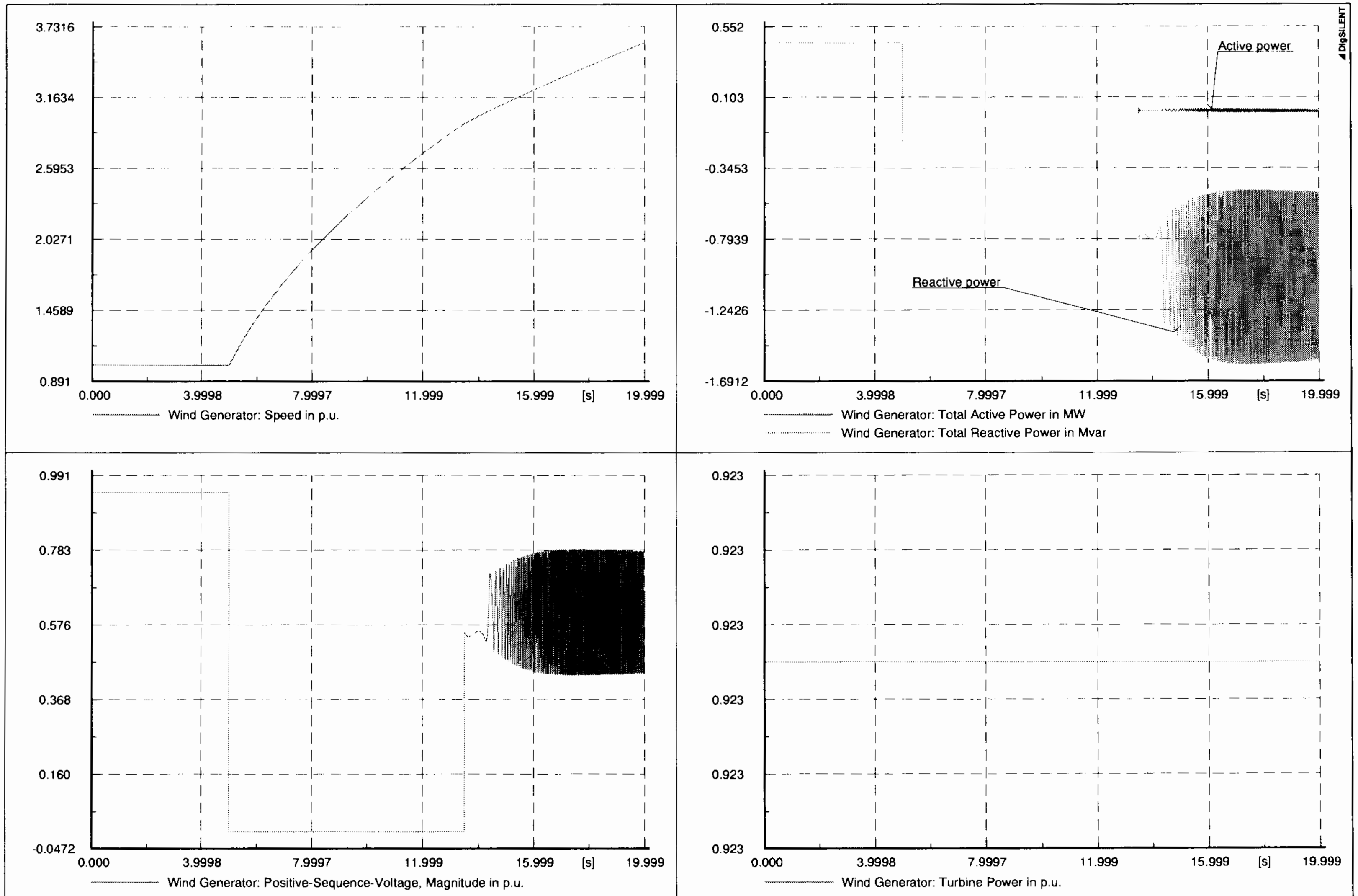




UCT	Three phase fault at the end of the 5km feeder, dt=8501.3msec	Hydro gen	Date: 12/10/2001 Annex: A /1


3.5693
3.0351
2.5010
1.9668
1.4327
0.899
0.000
3.9931
7.9862
11.979
15.972
[s]
19.966
Wind Generator: Speed in p.u.
0.568
Active power
0.047
-0.4742
-0.9956
Reactive power
-1.5170
-2.0383
Wind Generator: Total Active Power in MW
Wind Generator: Total Reactive Power in Mvar
DIgSILENT
0.991
0.783
0.576
0.368
0.160
-0.0472
Wind Generator: Positive-Sequence-Voltage, Magnitude in p.u.
0.923
Wind Generator: Turbine Power in p.u.
UCT
Three phase fault at the end of the 5km feeder, dt=8501.3msec
Wind gen
Date: 12/10/2001
Annex: A /2


1.6606
1.5204
1.3802
1.2399
1.0997
0.960
0.000
3.9998
7.9997
11.999
15.999
[s]
19.999
Hydro Generator: Speed in p.u.
197.94
118.77
39.601
-39.569
-118.74
-197.91
Hydro Generator: Rotor angle with reference to reference machine angle in deg
DIgSILENT
3.4729
3.2588
3.0447
2.8307
2.6166
2.4025
Hydro Generator: Excitation Voltage in p.u.
0.976
0.772
0.568
0.364
0.161
-0.0433
Hydro Generator: Turbine Power in p.u.
UCT
Three phase fault at the end of the 5km feeder, dt=8501.4msec
Hydro gen
Date: 12/10/2001
Annex: A /1



UCT	Three phase fault at the end of the 5km feeder, dt=8501.4msec	Wind gen	Date: 12/10/2001 Annex: A /2

APPENDIX B

ELECTRICAL DATA FOR CASE STUDY 2
&
SIMULATION RESULTS

Synchronous Generator

Rated Voltage	0.4kV
Rated MW	1MW
Power factor	0.9
Connection	YN
Stator resistance [r_s]	0.051716
Leakage Reactance [X_l]	0.19
Xd	0.94
Xq	0.61
X'd	0.25
X'q	0.21
X"d	0.22
X"q	0.2
Td'	3.512
T'q	0.333
T"d	0.0681275
T"q	0.02714286

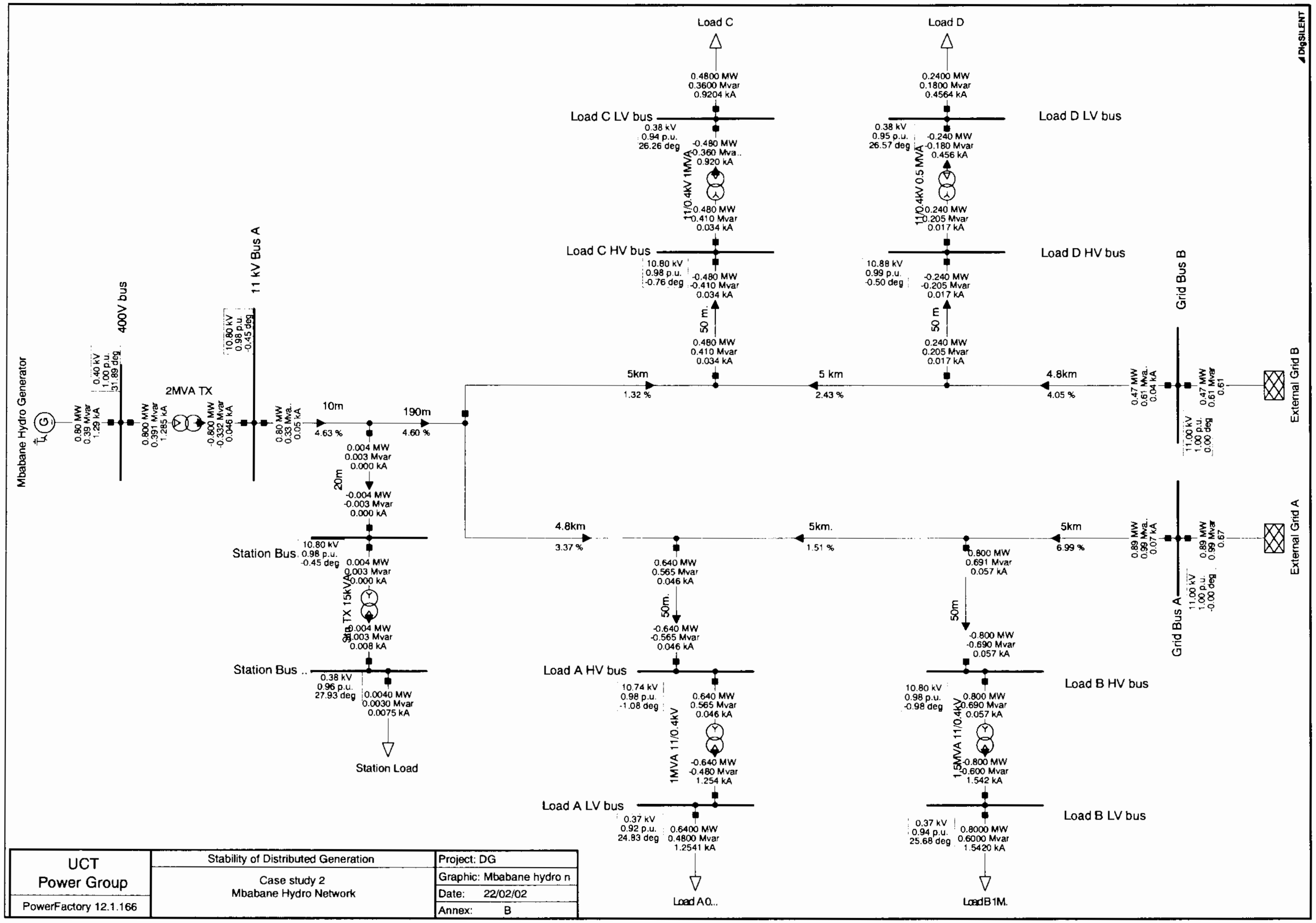
Governor (synchronous machine)

Tw	1
Qnl	0
Tg	0.2
Actual turbine power coeff [At]	1
Turbine nominal power [Pturb]	0
Dturb	0
R	0.04
Tf	0.01
Tr	0.05
Gmin	0
Gmax	1
Velm	0.16

Exciter (synchronus generator)

Tr	0
Kc	0.2
Tb	0
Tc	0
Ka	400
Ta	0.02
Te	0.8
Ke	1
E1	4.18

SE1	0.1
E2	0.03
SE2	3.14
Kd	0.38
Kf	0.03
Tf	1
Vrmin	-5.43
Vrmax	6.03



DIgSILENT
Load C
Load D
0.4800 MW
0.3600 Mvar
0.9204 kA
0.2400 MW
0.1800 Mvar
0.4564 kA
Load C LV bus
Load D LV bus
0.38 kV
0.94 p.u.
26.26 deg
0.38 kV
0.95 p.u.
26.57 deg
-0.480 MW
-0.360 Mva..
0.920 kA
-0.240 MW
-0.180 Mvar
0.456 kA
11/0.4kV 1MVA
11/0.4kV 0.5 MVA
0.480 MW
0.410 Mvar
0.034 kA
0.240 MW
0.205 Mvar
0.017 kA
Load C HV bus
Load D HV bus
10.80 kV
0.98 p.u.
-0.76 deg
10.88 kV
0.99 p.u.
-0.50 deg
-0.480 MW
-0.410 Mvar
0.034 kA
-0.240 MW
-0.205 Mvar
0.017 kA
50 m.
50 m
0.480 MW
0.410 Mvar
0.034 kA
0.240 MW
0.205 Mvar
0.017 kA
5km
1.32 %
5 km
2.43 %
4.8km
4.05 %
Grid Bus B
0.47 MW
0.61 Mva..
0.04 kA
0.47 MW
0.61 Mvar
0.61
11.00 kV
1.00 p.u.
0.00 deg
External Grid B
Mbabane Hydro Generator
0.80 MW
0.39 Mvar
1.29 kA
400V bus
0.40 kV
1.00 p.u.
31.89 deg
2MVA TX
0.800 MW
0.391 Mvar
1.285 kA
-0.800 MW
-0.332 Mvar
0.046 kA
11 kV Bus A
10.80 kV
0.98 p.u.
-0.45 deg
0.80 MW
0.33 Mva..
0.05 kA
10m
4.63 %
190m
4.60 %
0.004 MW
0.003 Mvar
0.000 kA
20m
-0.004 MW
-0.003 Mvar
0.000 kA
Station Bus.
10.80 kV
0.98 p.u.
-0.45 deg
0.004 MW
0.003 Mvar
0.000 kA
TX 15KVA
-0.004 MW
-0.003 Mvar
0.008 kA
Station Bus ..
0.38 kV
0.96 p.u.
27.93 deg
0.0040 MW
0.0030 Mvar
0.0075 kA
Station Load
4.8km
3.37 %
5km.
1.51 %
5km
6.99 %
Grid Bus A
0.89 MW
0.99 Mva..
0.07 kA
0.89 MW
0.99 Mvar
0.67
11.00 kV
1.00 p.u.
-0.00 deg
External Grid A
0.640 MW
0.565 Mvar
0.046 kA
50m.
-0.640 MW
-0.565 Mvar
0.046 kA
0.800 MW
0.691 Mvar
0.057 kA
50m
-0.800 MW
-0.690 Mvar
0.057 kA
Load A HV bus
10.74 kV
0.98 p.u.
-1.08 deg
0.640 MW
0.565 Mvar
0.046 kA
1MVA 11/0.4kV
-0.640 MW
-0.480 Mvar
1.254 kA
Load B HV bus
10.80 kV
0.98 p.u.
-0.98 deg
0.800 MW
0.690 Mvar
0.057 kA
1.5MVA 11/0.4kV
-0.800 MW
-0.600 Mvar
1.542 kA
Load A LV bus
0.37 kV
0.92 p.u.
24.83 deg
0.6400 MW
0.4800 Mvar
1.2541 kA
Load B LV bus
0.37 kV
0.94 p.u.
25.68 deg
0.8000 MW
0.6000 Mvar
1.5420 kA
Load A0...
LoadB1M.
UCT
Power Group
PowerFactory 12.1.166
Stability of Distributed Generation
Case study 2
Mbabane Hydro Network
Project: DG
Graphic: Mbabane hydro n
Date: 22/02/02
Annex: B

APPENDIX C

ELECTRICAL DATA FOR CHAPTER 7 & SIMULATION RESULTS

Synchronous Generator

Rated Voltage	11kV
Rated MW	14MW
Power factor	0.8
Connection	YN
Stator resistance [r_s]	0.04
Leakage Reactance [X_l]	0.0163
Inertia constant, sec	3.675
Xd	1.2
Xq	0.9
X'd	0.355
X'q	
X"d	0.12
X"q	
Td'	1.5
T'q	
T"d	0.01
T"q	0.01

Governor (synchronous machine)

Tw	1
Qnl	0
Tg	0.2
Actual turbine power coeff [At]	1
Turbine nominal power [Pturb]	0
Dturb	0
R	0.04
Tf	0.01
Tr	0.05
Gmin	0
Gmax	1
Velm	0.16

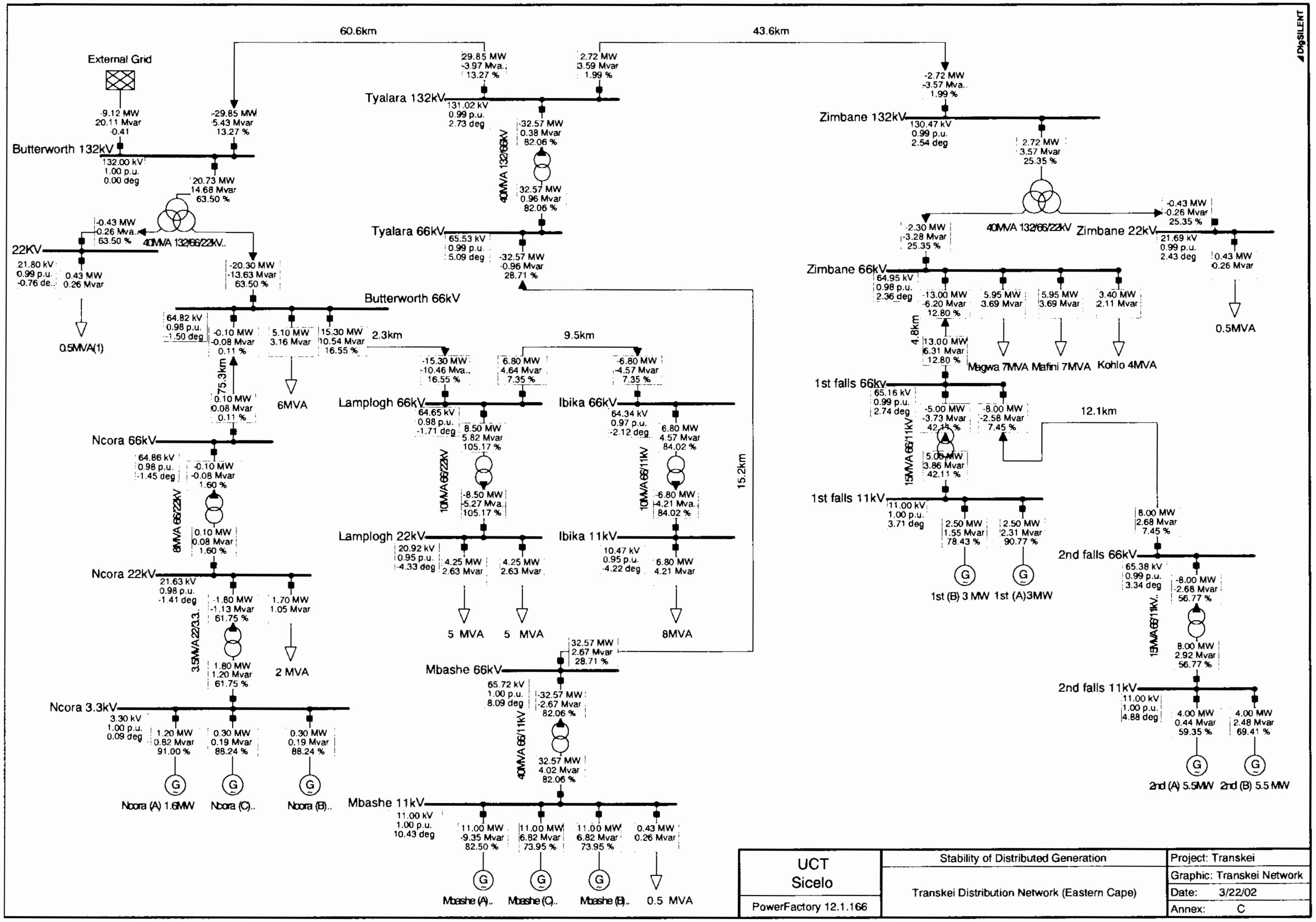
Exciter (synchronus generator)

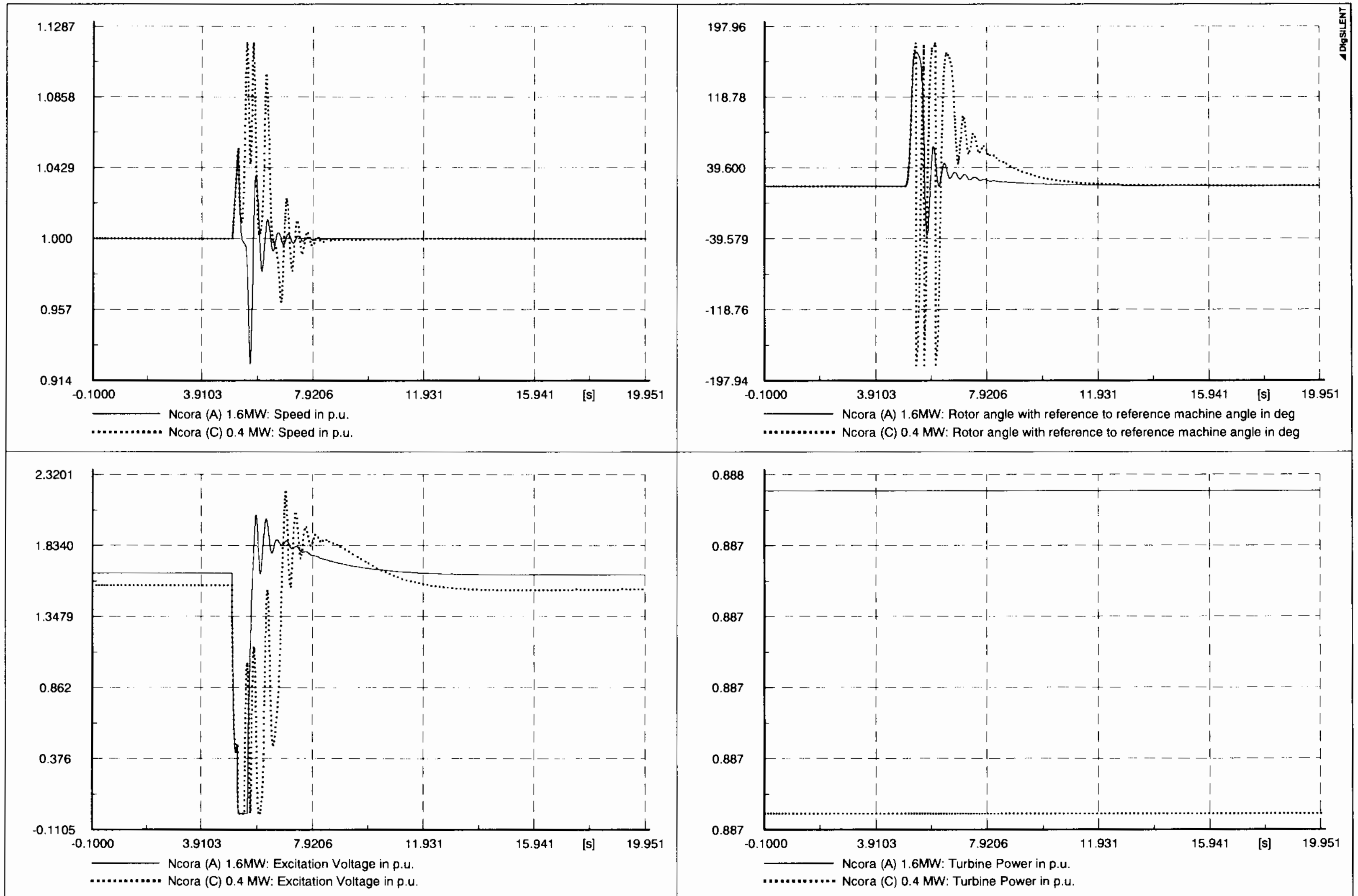
Tr	0
Kc	0.2
Tb	10
Tc	0
Ka	200
Ta	0.1

Te	0.05
Ke	1
E1	4.18
SE1	0.1
E2	0.03
SE2	3.14
Kd	0.38
Kf	0.03
Tf	1
Vrmin	-5.43
Vrmax	6.03

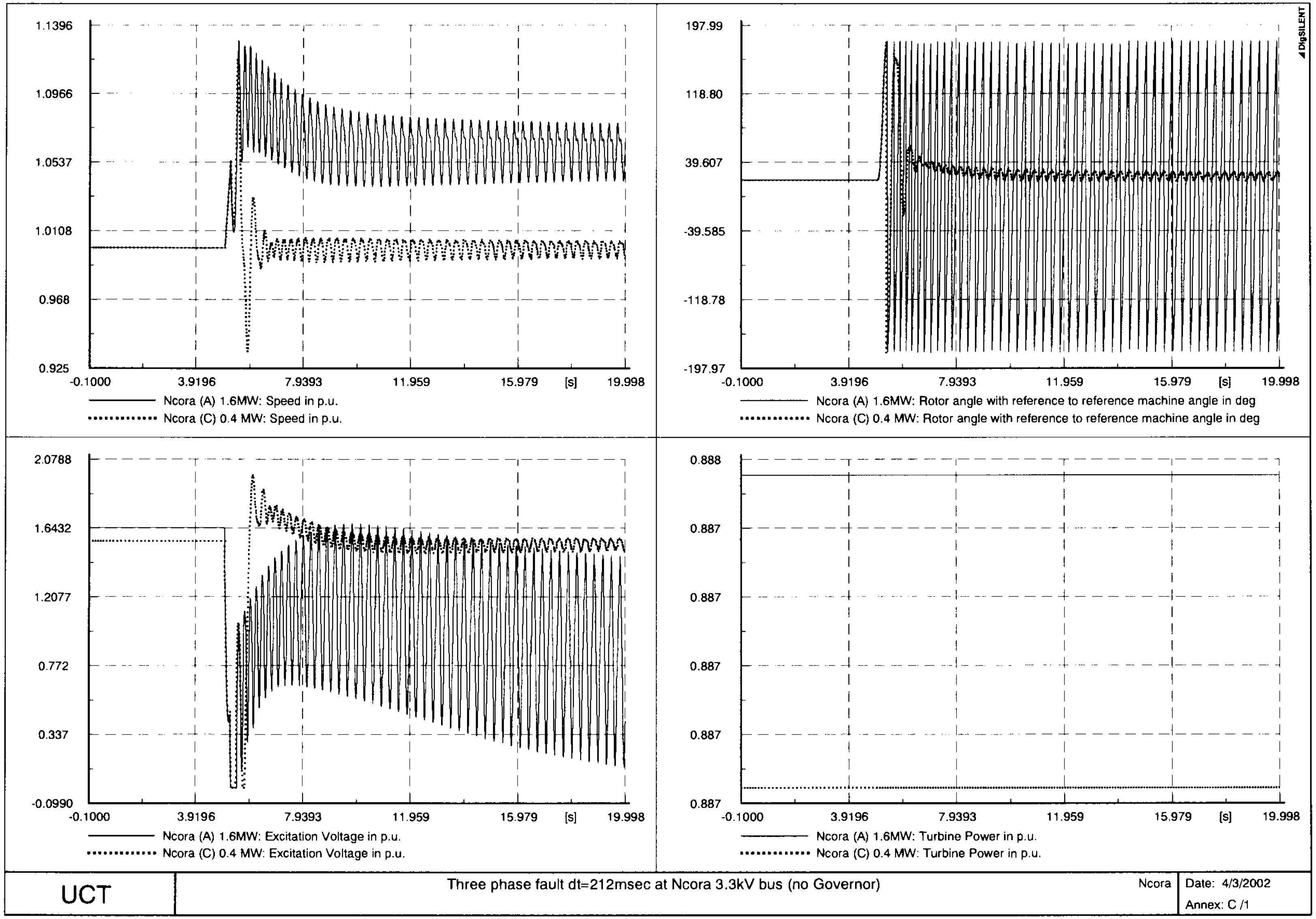
Induction Generator

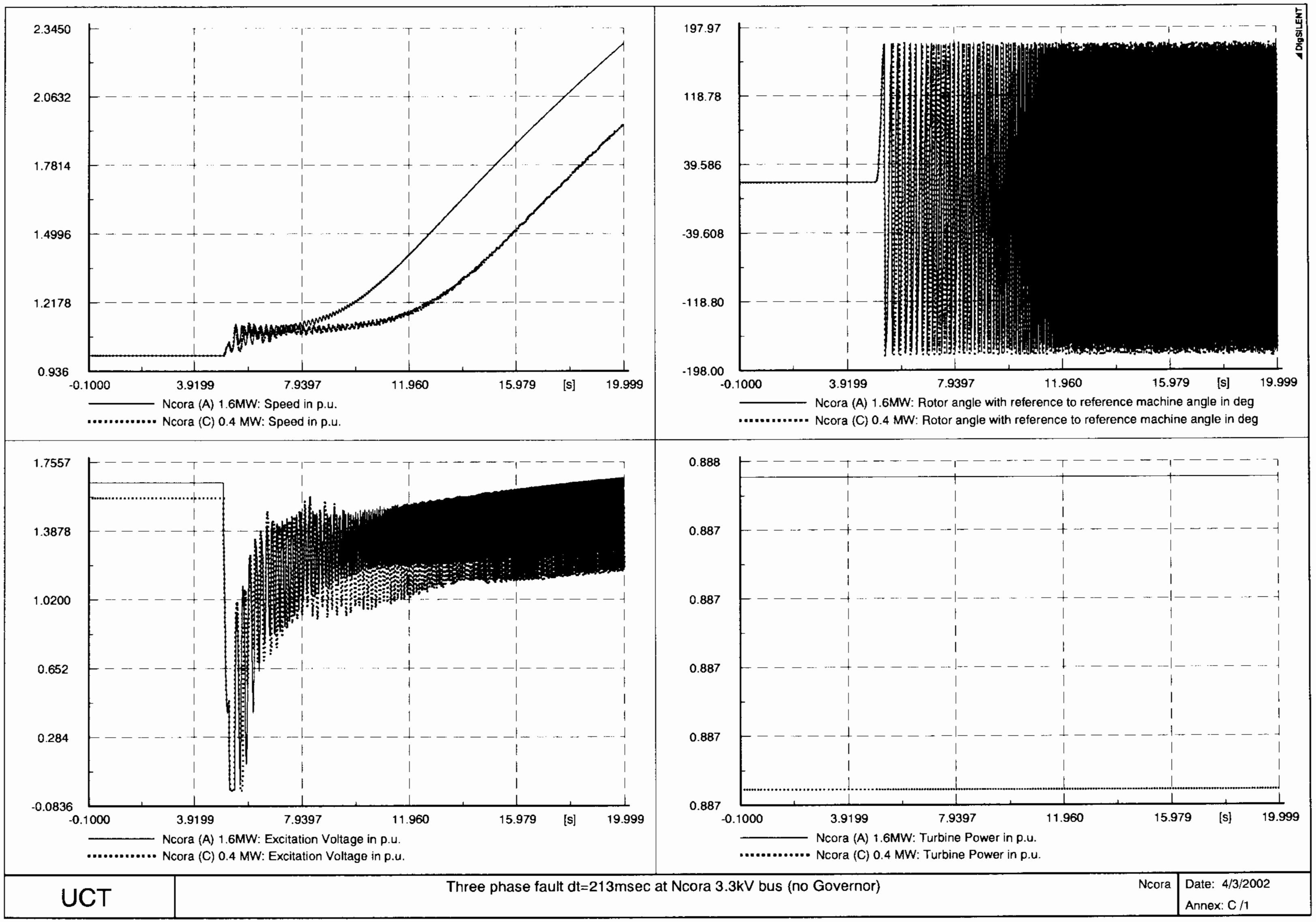
Rated Voltage	11kV
Rated MW	0.5MW
No of pole pairs	1
Connection	D
Rotor	Single Cage
Stator resistance [Rs]	0.0054
Mag. Reactance [Xm]	4.34 p.u.
Stator Reactance [Xs]	0.0852 p.u.
Rotor Resistance [R_{rA}]	0.0206 p.u.
Rotor Reactance [X_{rA}]	0.139 p.u.
Acc. Time constant	2 secs


60.6km
43.6km
External Grid
Butterworth 132kV
22KV
0.5MVA(1)
Tyalara 132kV
Tyalara 66kV
40MVA 132/66kV
40MVA 132/66/22kV..
Butterworth 66kV
2.3km
9.5km
6MVA
75.3km
Ncora 66kV
8MVA 66/22kV
Ncora 22kV
3.5MVA/22/3.3..
2 MVA
Ncora 3.3kV
Ncora (A) 1.6MW
Ncora (C)..
Ncora (B)..
Lamplogh 66kV
10MVA 66/22kV
Lamplogh 22kV
5 MVA
5 MVA
Ibika 66kV
10MVA 66/11kV
Ibika 11kV
8MVA
15.2km
Mbashe 66kV
40MVA 66/11kV
Mbashe 11kV
Mbashe (A)..
Mbashe (C)..
Mbashe (B)..
0.5 MVA
Zimbane 132kV
40MVA 132/66/22kV
Zimbane 22kV
0.5MVA
Zimbane 66kV
4.8km
Magwa 7MVA
Mafini 7MVA
Kohlo 4MVA
1st falls 66kV
15MVA 66/11kV
12.1km
1st falls 11kV
1st (B) 3 MW
1st (A)3MW
2nd falls 66kV
15MVA 66/11kV..
2nd falls 11kV
2nd (A) 5.5MW
2nd (B) 5.5 MW
DIgSILENT
UCT
Sicelo
PowerFactory 12.1.166
Stability of Distributed Generation
Transkei Distribution Network (Eastern Cape)
Project: Transkei
Graphic: Transkei Network
Date: 3/22/02
Annex: C

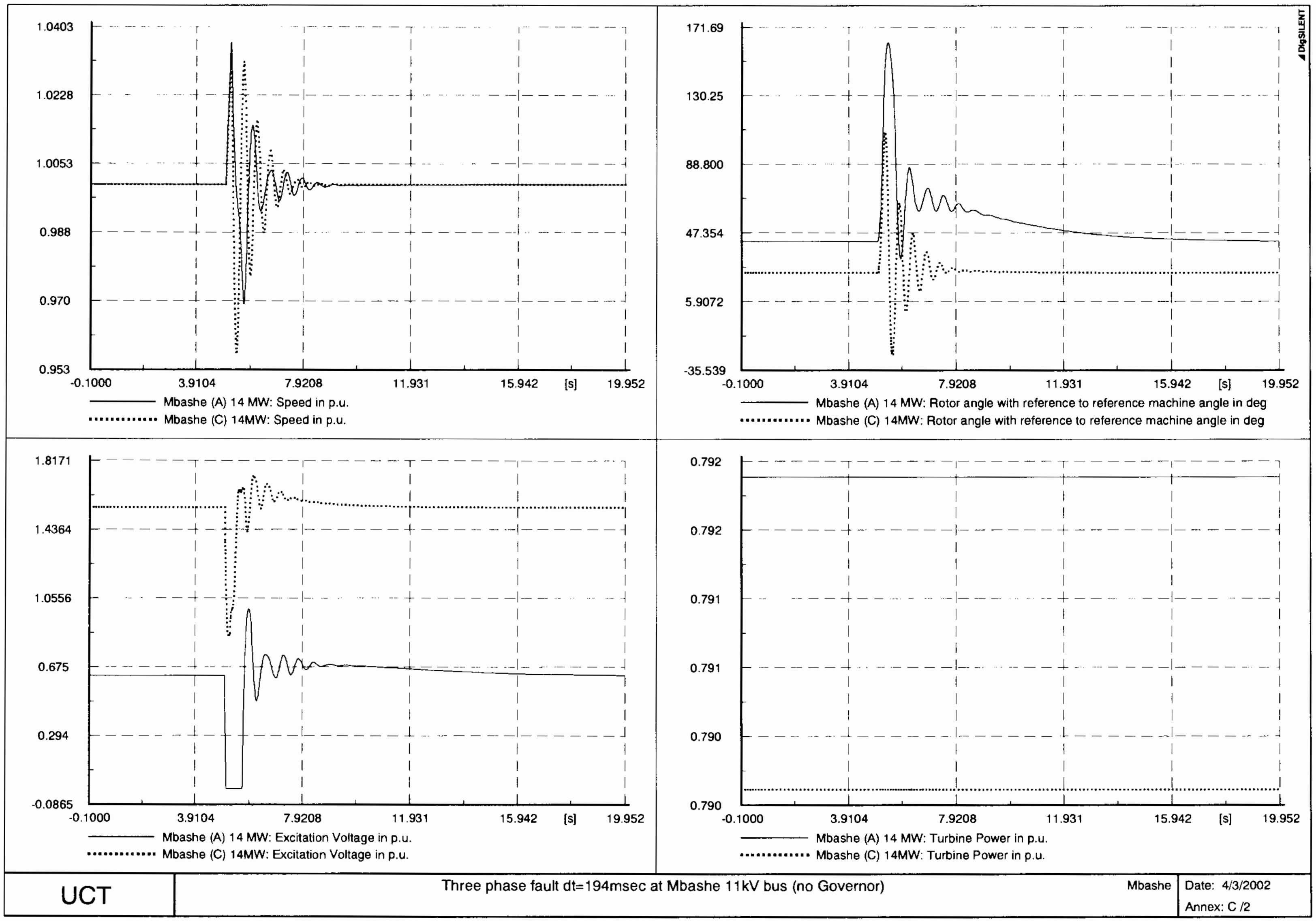


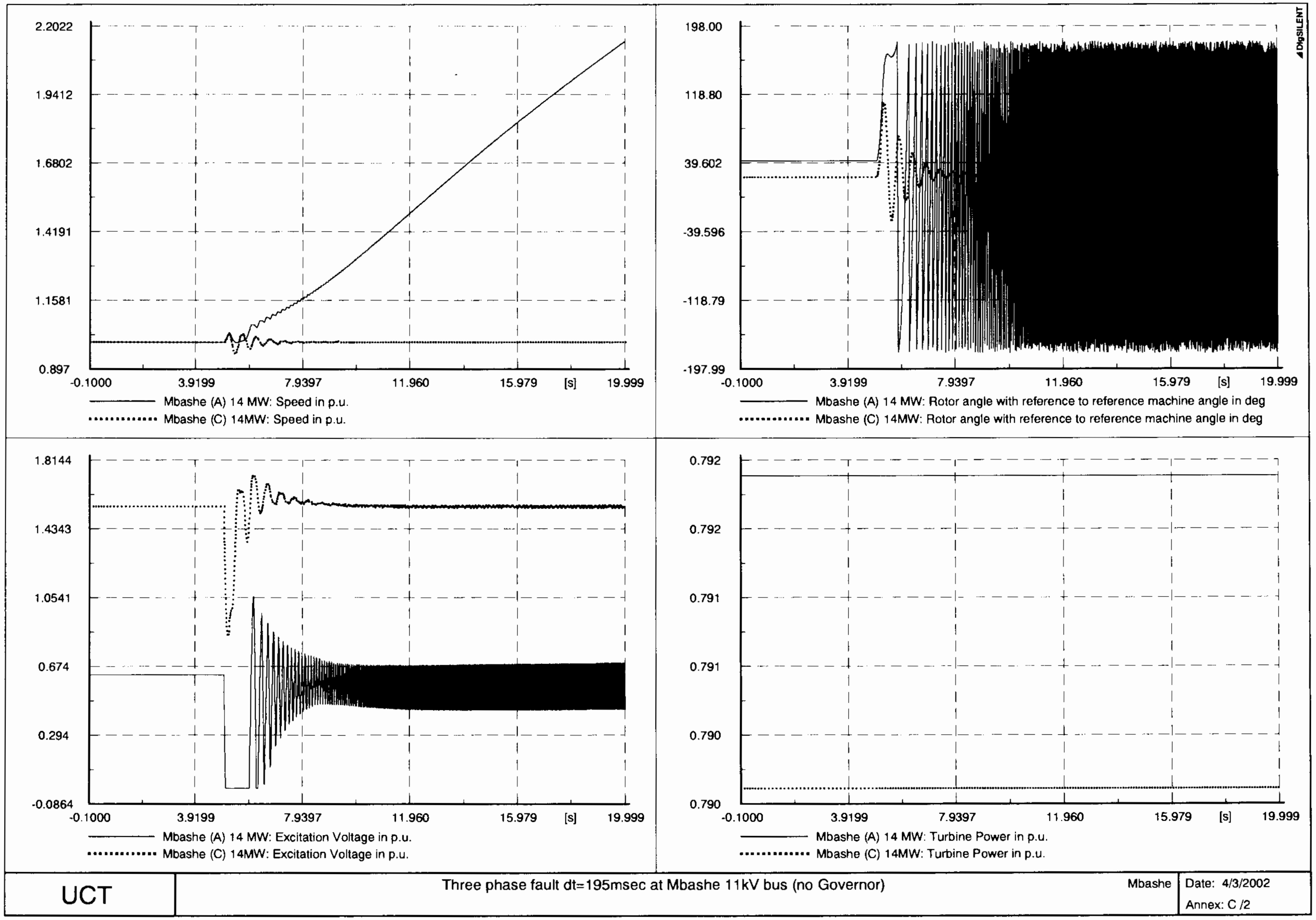
UCT	Three phase fault dt=211msec at Ncora 3.3kV bus (no Governor)	Ncora	Date: 4/3/2002 Annex: C /1

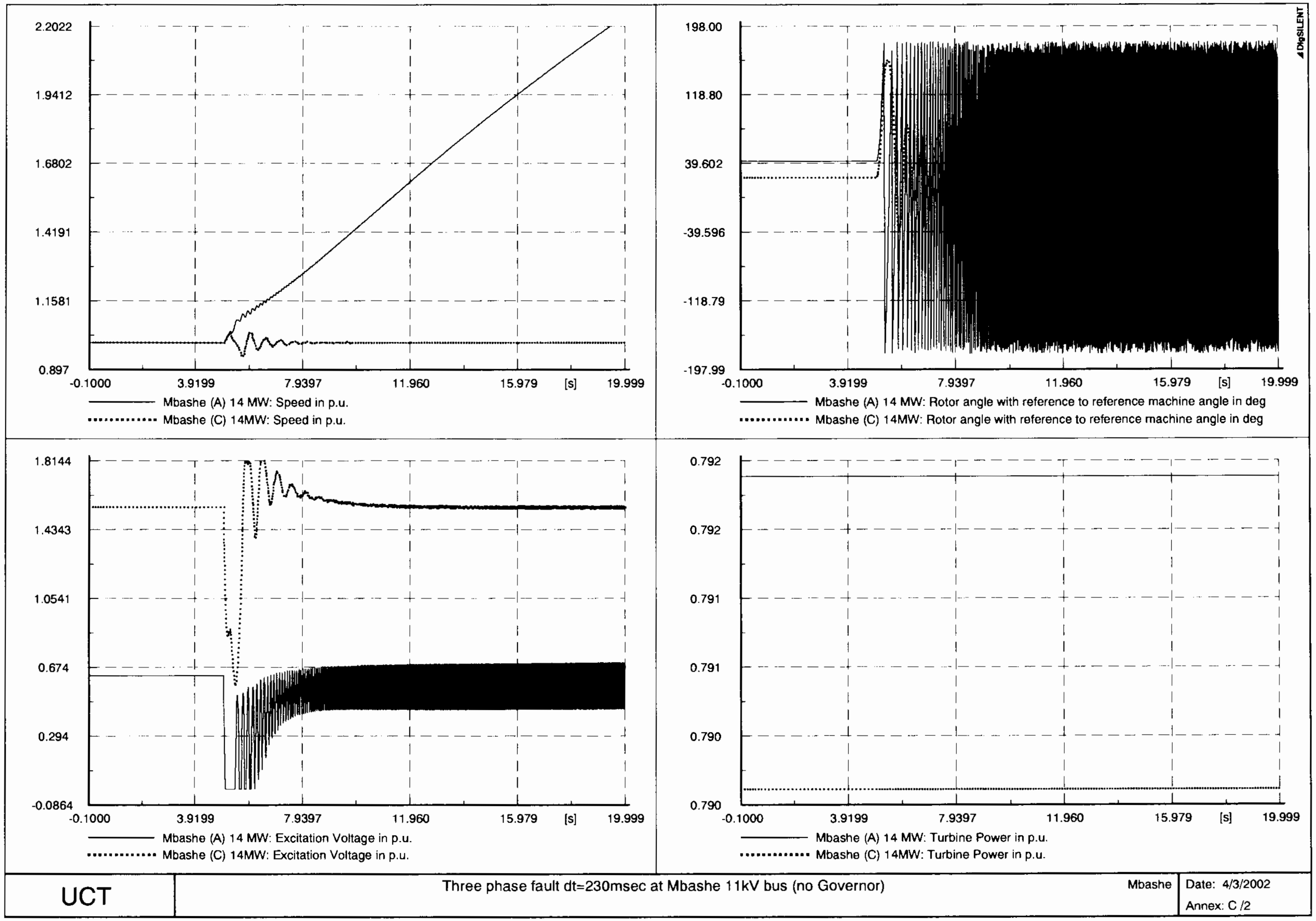

1.1396
1.0966
1.0537
1.0108
0.968
0.925
-0.1000
3.9196
7.9393
11.959
15.979
[s]
19.998
Ncora (A) 1.6MW: Speed in p.u.
Ncora (C) 0.4 MW: Speed in p.u.
197.99
118.80
39.607
-39.585
-118.78
-197.97
Ncora (A) 1.6MW: Rotor angle with reference to reference machine angle in deg
Ncora (C) 0.4 MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
2.0788
1.6432
1.2077
0.772
0.337
-0.0990
Ncora (A) 1.6MW: Excitation Voltage in p.u.
Ncora (C) 0.4 MW: Excitation Voltage in p.u.
0.888
0.887
0.887
0.887
0.887
0.887
Ncora (A) 1.6MW: Turbine Power in p.u.
Ncora (C) 0.4 MW: Turbine Power in p.u.
UCT
Three phase fault dt=212msec at Ncora 3.3kV bus (no Governor)
Ncora
Date: 4/3/2002
Annex: C /1



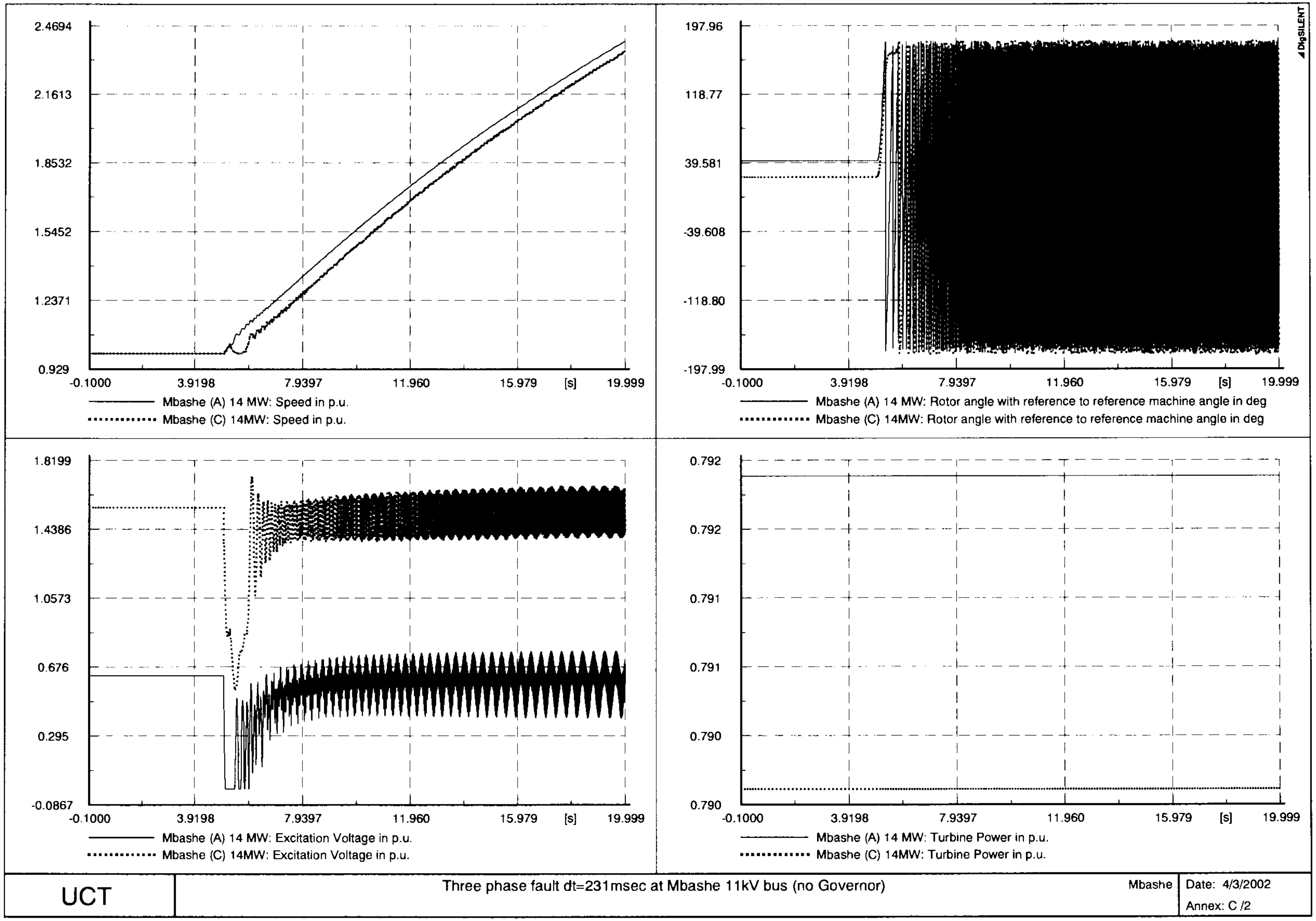
2.3450
2.0632
1.7814
1.4996
1.2178
0.936
-0.1000
3.9199
7.9397
11.960
15.979
[s]
19.999
Ncora (A) 1.6MW: Speed in p.u.
Ncora (C) 0.4 MW: Speed in p.u.
197.97
118.78
39.586
-39.608
-118.80
-198.00
Ncora (A) 1.6MW: Rotor angle with reference to reference machine angle in deg
Ncora (C) 0.4 MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
1.7557
1.3878
1.0200
0.652
0.284
-0.0836
Ncora (A) 1.6MW: Excitation Voltage in p.u.
Ncora (C) 0.4 MW: Excitation Voltage in p.u.
0.888
0.887
Ncora (A) 1.6MW: Turbine Power in p.u.
Ncora (C) 0.4 MW: Turbine Power in p.u.
UCT
Three phase fault dt=213msec at Ncora 3.3kV bus (no Governor)
Ncora
Date: 4/3/2002
Annex: C /1


DIgSILENT
1.0403
1.0228
1.0053
0.988
0.970
0.953
-0.1000
3.9104
7.9208
11.931
15.942
[s]
19.952
Mbashe (A) 14 MW: Speed in p.u.
Mbashe (C) 14MW: Speed in p.u.
171.69
130.25
88.800
47.354
5.9072
-35.539
Mbashe (A) 14 MW: Rotor angle with reference to reference machine angle in deg
Mbashe (C) 14MW: Rotor angle with reference to reference machine angle in deg
1.8171
1.4364
1.0556
0.675
0.294
-0.0865
Mbashe (A) 14 MW: Excitation Voltage in p.u.
Mbashe (C) 14MW: Excitation Voltage in p.u.
0.792
0.792
0.791
0.791
0.790
0.790
Mbashe (A) 14 MW: Turbine Power in p.u.
Mbashe (C) 14MW: Turbine Power in p.u.
UCT
Three phase fault dt=194msec at Mbashe 11kV bus (no Governor)
Mbashe
Date: 4/3/2002
Annex: C /2

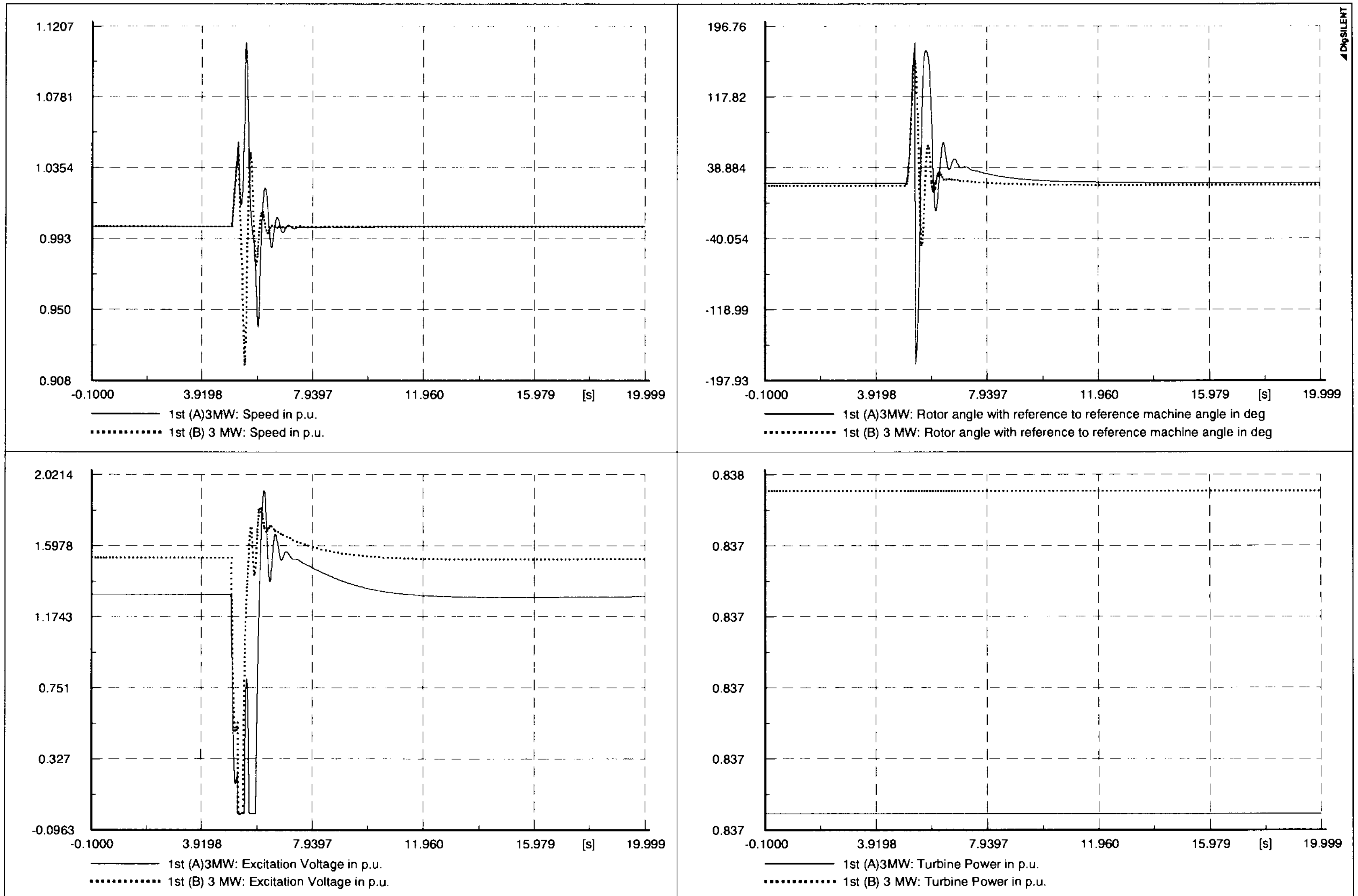

2.2022
1.9412
1.6802
1.4191
1.1581
0.897
-0.1000
3.9199
7.9397
11.960
15.979
[s]
19.999
Mbashe (A) 14 MW: Speed in p.u.
Mbashe (C) 14MW: Speed in p.u.
198.00
118.80
39.602
-39.596
-118.79
-197.99
Mbashe (A) 14 MW: Rotor angle with reference to reference machine angle in deg
Mbashe (C) 14MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
1.8144
1.4343
1.0541
0.674
0.294
-0.0864
Mbashe (A) 14 MW: Excitation Voltage in p.u.
Mbashe (C) 14MW: Excitation Voltage in p.u.
0.792
0.792
0.791
0.791
0.790
0.790
Mbashe (A) 14 MW: Turbine Power in p.u.
Mbashe (C) 14MW: Turbine Power in p.u.
UCT
Three phase fault dt=195msec at Mbashe 11kV bus (no Governor)
Mbashe
Date: 4/3/2002
Annex: C /2



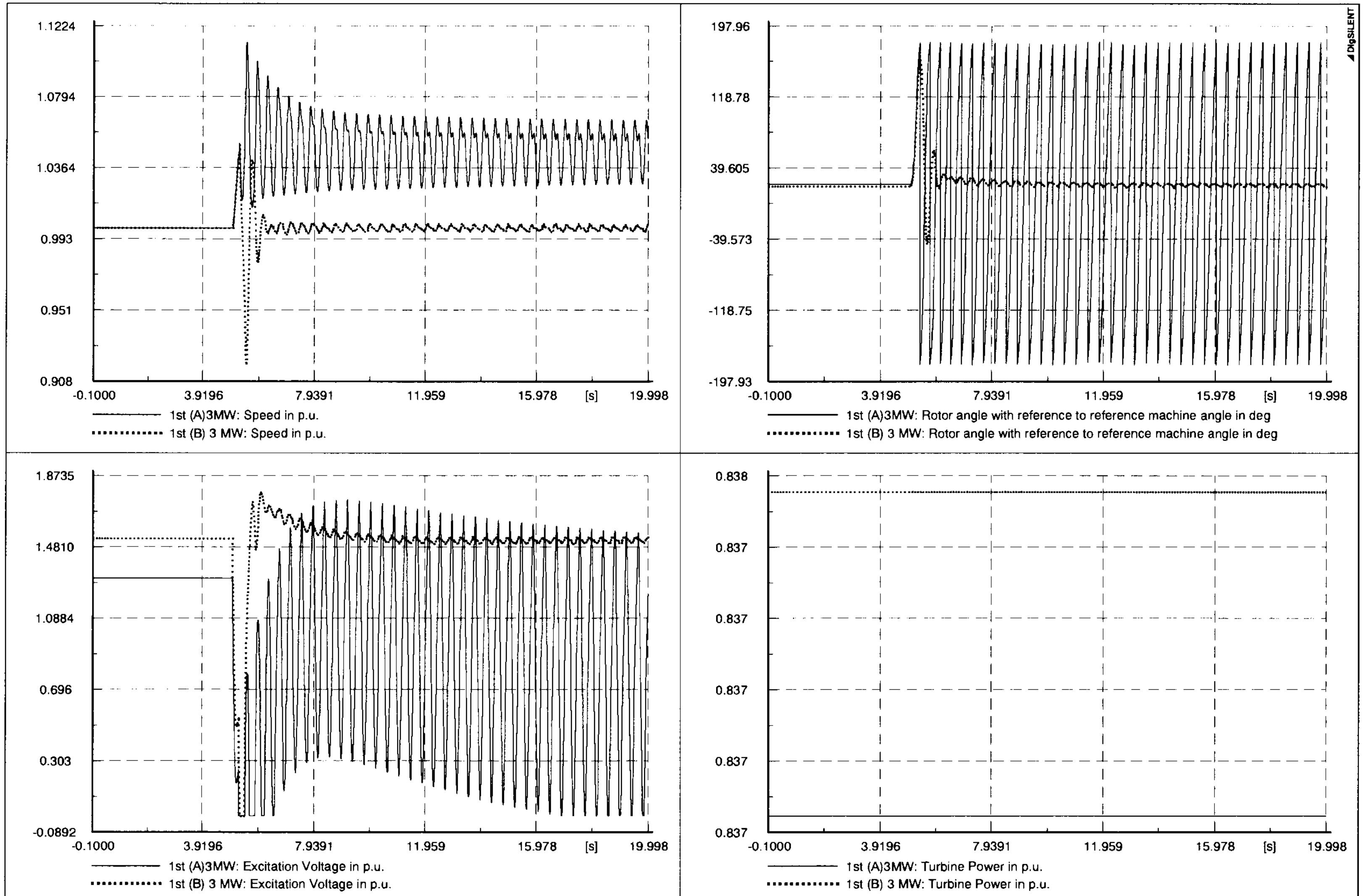
2.2022
1.9412
1.6802
1.4191
1.1581
0.897
-0.1000
3.9199
7.9397
11.960
15.979
[s]
19.999
Mbashe (A) 14 MW: Speed in p.u.
Mbashe (C) 14MW: Speed in p.u.
198.00
118.80
39.602
-39.596
-118.79
-197.99
Mbashe (A) 14 MW: Rotor angle with reference to reference machine angle in deg
Mbashe (C) 14MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
1.8144
1.4343
1.0541
0.674
0.294
-0.0864
Mbashe (A) 14 MW: Excitation Voltage in p.u.
Mbashe (C) 14MW: Excitation Voltage in p.u.
0.792
0.792
0.791
0.791
0.790
0.790
Mbashe (A) 14 MW: Turbine Power in p.u.
Mbashe (C) 14MW: Turbine Power in p.u.
UCT
Three phase fault dt=230msec at Mbashe 11kV bus (no Governor)
Mbashe
Date: 4/3/2002
Annex: C /2



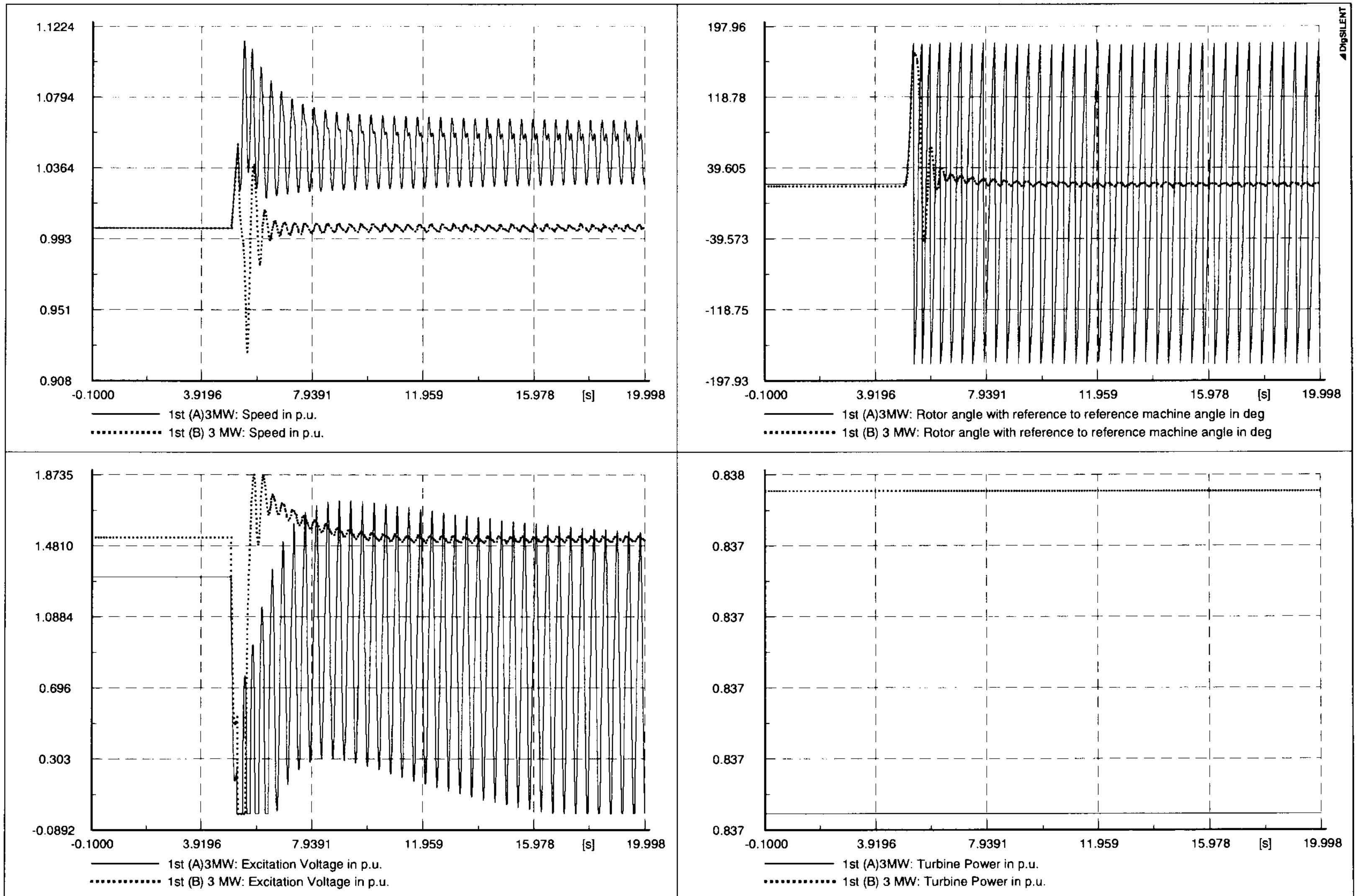
2.4694
2.1613
1.8532
1.5452
1.2371
0.929
-0.1000
3.9198
7.9397
11.960
15.979
[s]
19.999
Mbashe (A) 14 MW: Speed in p.u.
Mbashe (C) 14MW: Speed in p.u.
197.96
118.77
39.581
-39.608
-118.80
-197.99
Mbashe (A) 14 MW: Rotor angle with reference to reference machine angle in deg
Mbashe (C) 14MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
1.8199
1.4386
1.0573
0.676
0.295
-0.0867
Mbashe (A) 14 MW: Excitation Voltage in p.u.
Mbashe (C) 14MW: Excitation Voltage in p.u.
0.792
0.792
0.791
0.791
0.790
0.790
Mbashe (A) 14 MW: Turbine Power in p.u.
Mbashe (C) 14MW: Turbine Power in p.u.
UCT
Three phase fault dt=231msec at Mbashe 11kV bus (no Governor)
Mbashe
Date: 4/3/2002
Annex: C /2



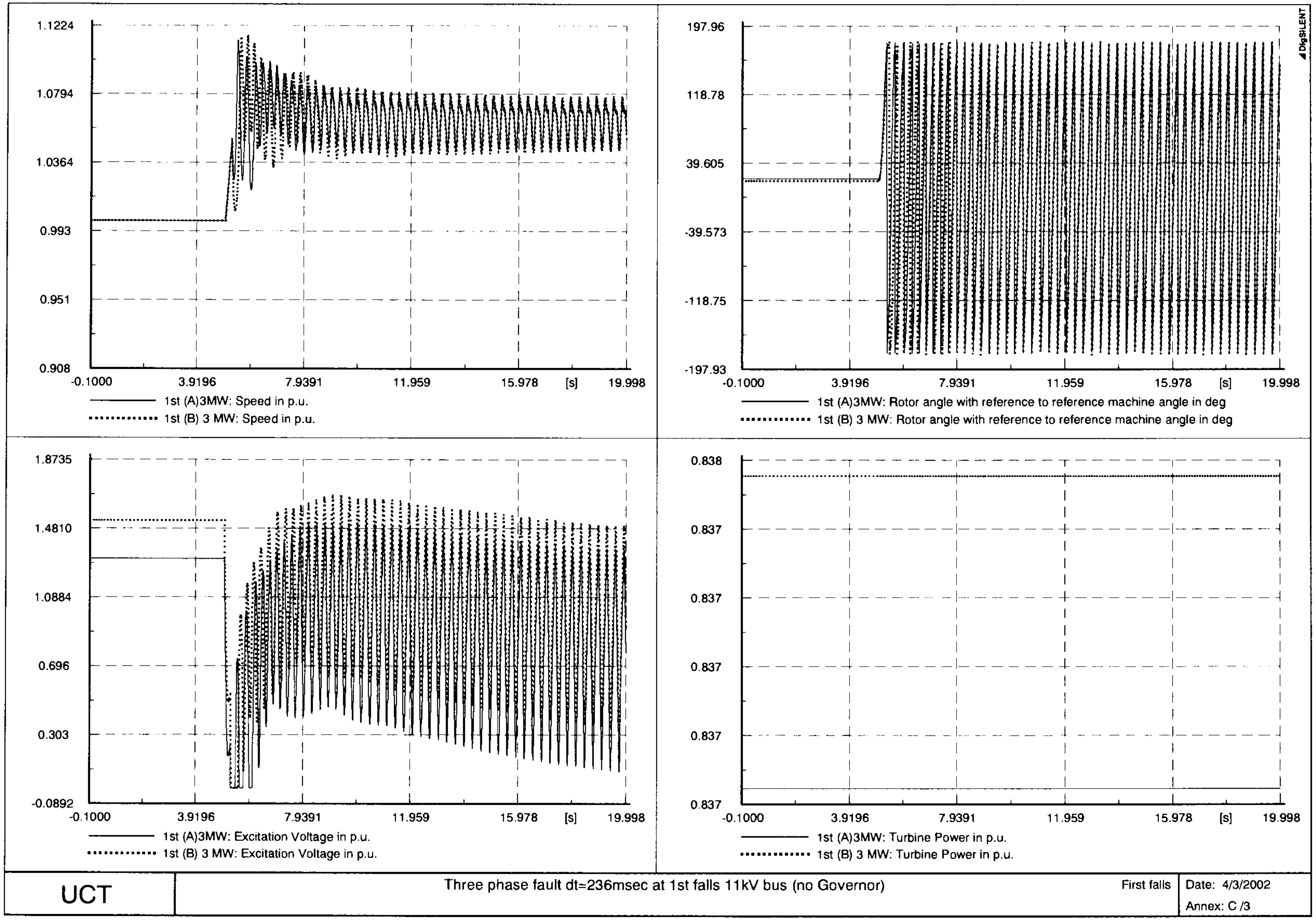
UCT	Three phase fault dt=232msec at 1st falls 11kV bus (no Governor)	First falls	Date: 4/3/2002 Annex: C /3

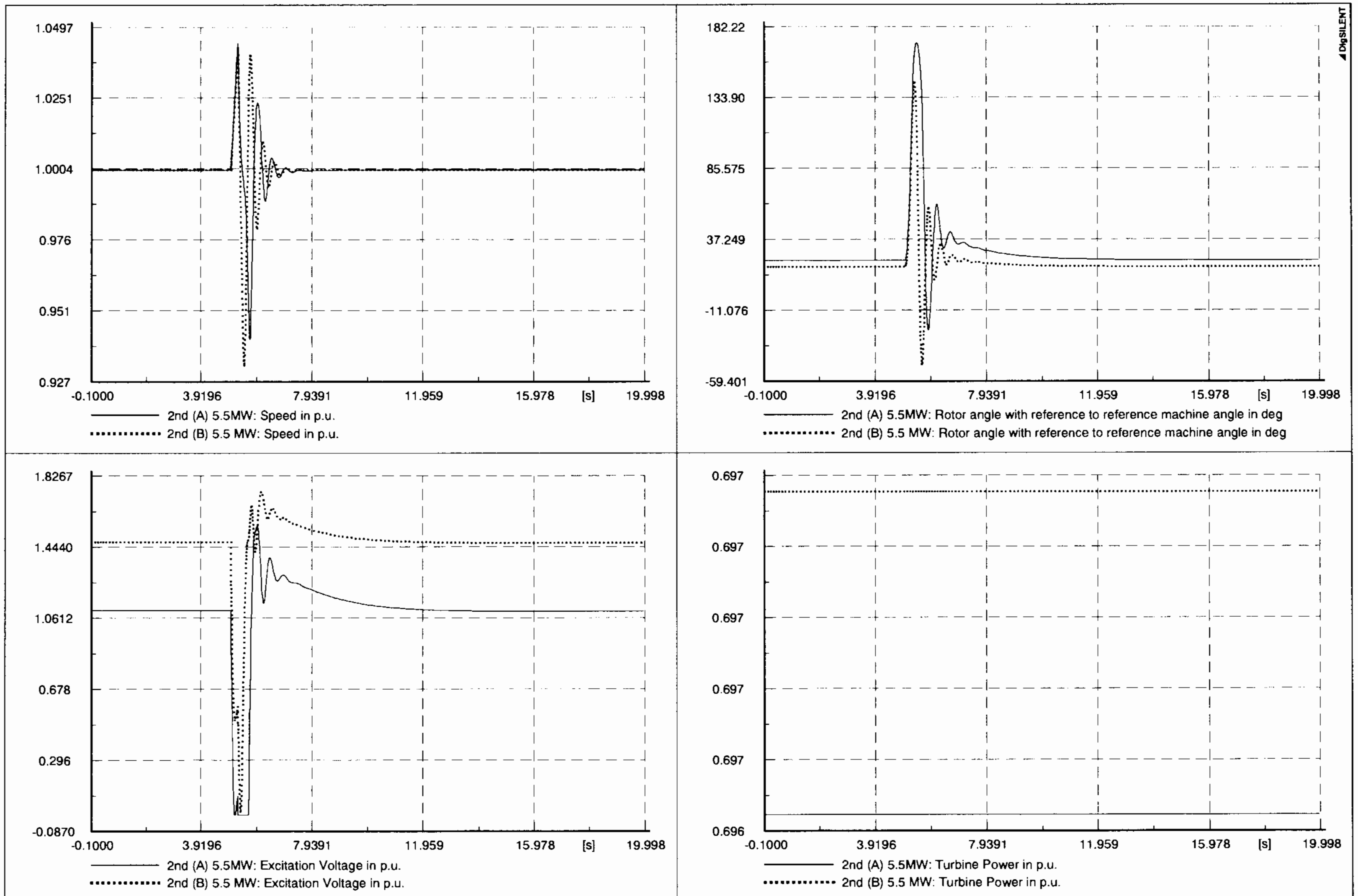


UCT	Three phase fault dt=233msec at 1st falls 11kV bus (no Governor)	First falls	Date: 4/3/2002 Annex: C /3

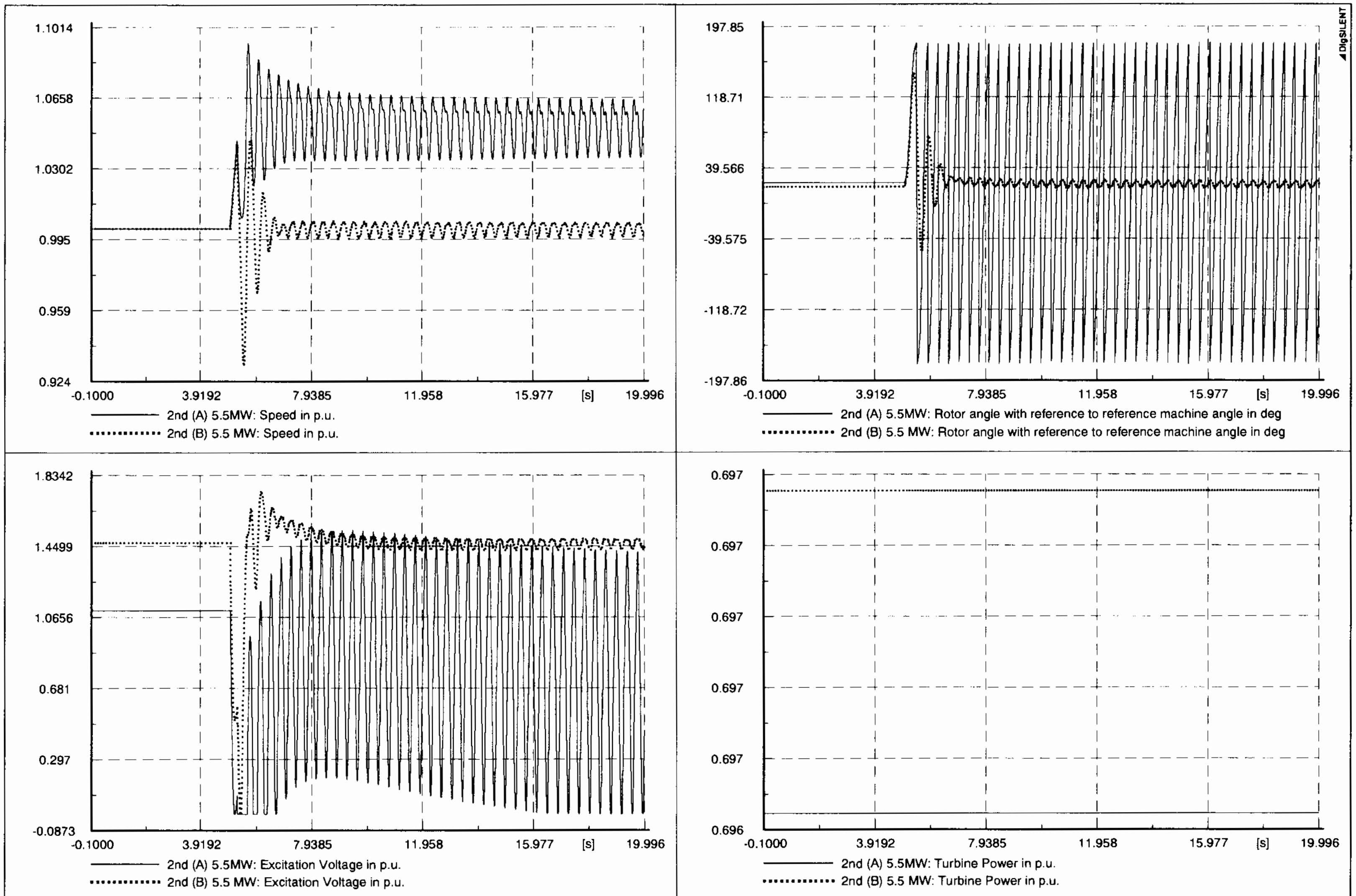


UCT	Three phase fault dt=235msec at 1st falls 11kV bus (no Governor)	First falls	Date: 4/3/2002 Annex: C /3

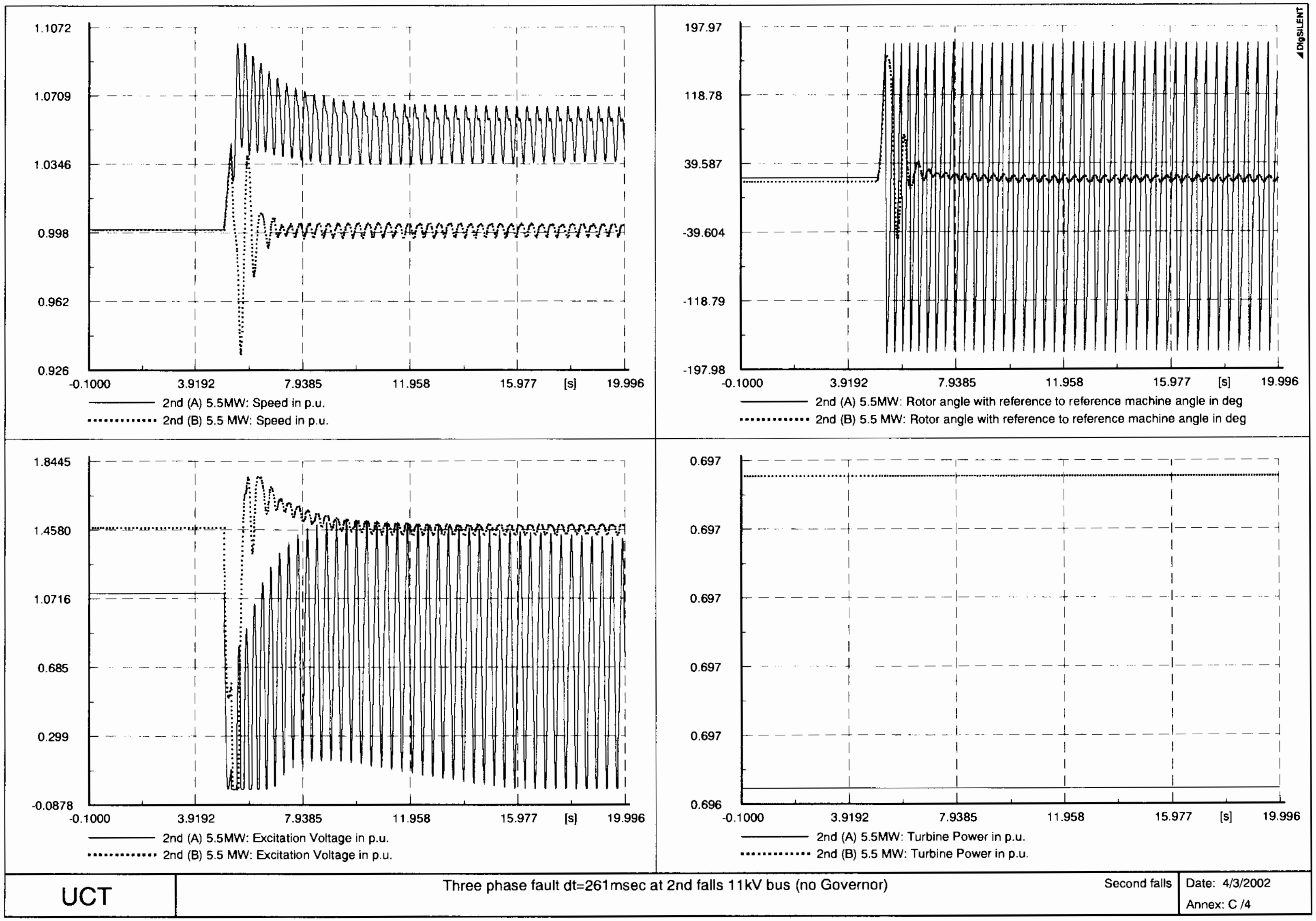

1.1224
1.0794
1.0364
0.993
0.951
0.908
-0.1000
3.9196
7.9391
11.959
15.978
[s]
19.998
1st (A)3MW: Speed in p.u.
1st (B) 3 MW: Speed in p.u.
197.96
118.78
39.605
-39.573
-118.75
-197.93
1st (A)3MW: Rotor angle with reference to reference machine angle in deg
1st (B) 3 MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
1.8735
1.4810
1.0884
0.696
0.303
-0.0892
1st (A)3MW: Excitation Voltage in p.u.
1st (B) 3 MW: Excitation Voltage in p.u.
0.838
0.837
1st (A)3MW: Turbine Power in p.u.
1st (B) 3 MW: Turbine Power in p.u.
UCT
Three phase fault dt=236msec at 1st falls 11kV bus (no Governor)
First falls
Date: 4/3/2002
Annex: C /3

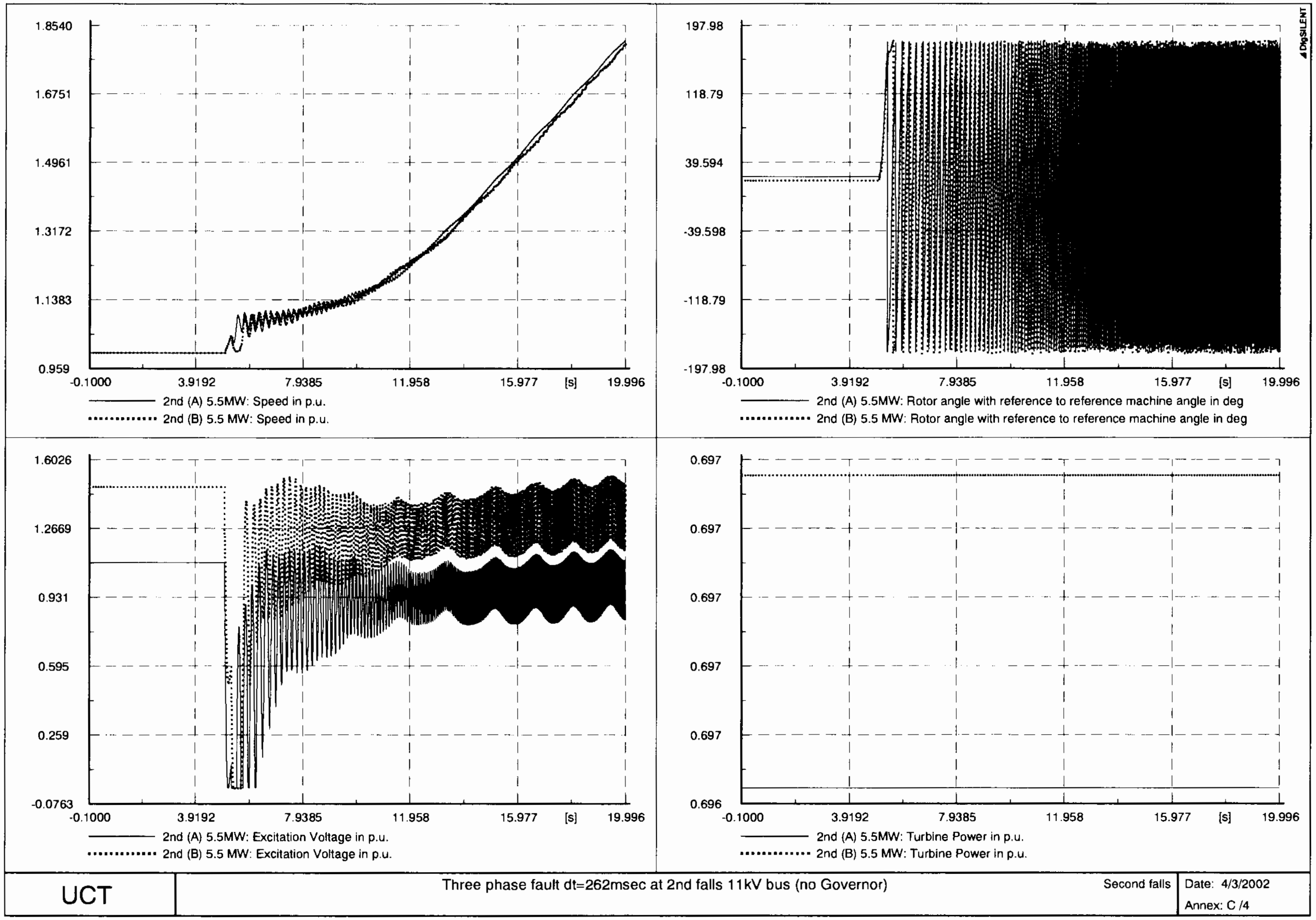


UCT	Three phase fault dt=252msec at 2nd falls 11kV bus (no Governor)	Second falls	Date: 4/3/2002 Annex: C /4



UCT	Three phase fault dt=253msec at 2nd falls 11kV bus (no Governor)	Second falls	Date: 4/3/2002 Annex: C /4


1.1072
1.0709
1.0346
0.998
0.962
0.926
-0.1000
3.9192
7.9385
11.958
15.977
[s]
19.996
2nd (A) 5.5MW: Speed in p.u.
2nd (B) 5.5 MW: Speed in p.u.
197.97
118.78
39.587
-39.604
-118.79
-197.98
2nd (A) 5.5MW: Rotor angle with reference to reference machine angle in deg
2nd (B) 5.5 MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
1.8445
1.4580
1.0716
0.685
0.299
-0.0878
2nd (A) 5.5MW: Excitation Voltage in p.u.
2nd (B) 5.5 MW: Excitation Voltage in p.u.
0.697
0.697
0.697
0.697
0.697
0.696
2nd (A) 5.5MW: Turbine Power in p.u.
2nd (B) 5.5 MW: Turbine Power in p.u.
UCT
Three phase fault dt=261msec at 2nd falls 11kV bus (no Governor)
Second falls
Date: 4/3/2002
Annex: C /4

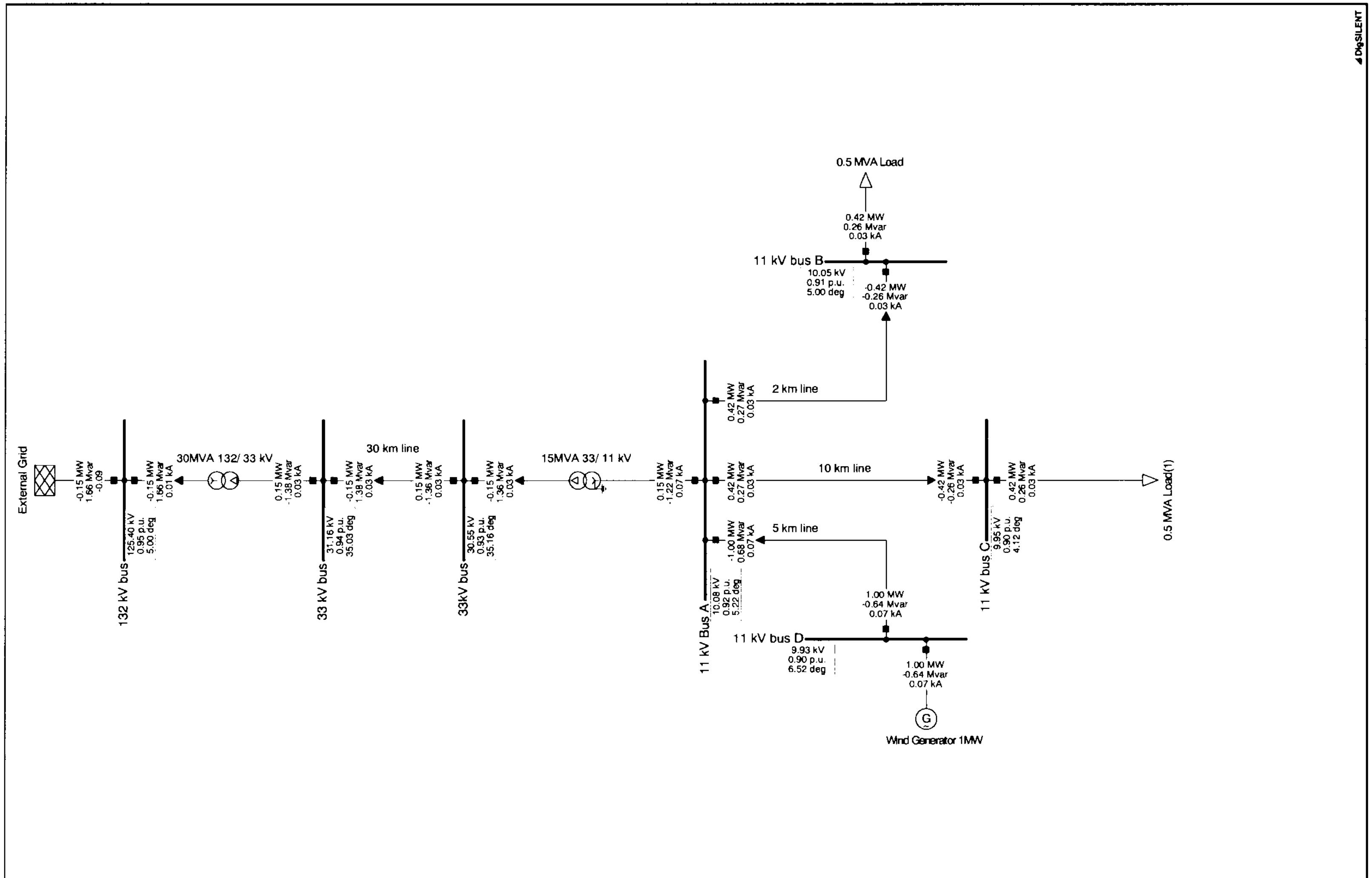

1.8540
1.6751
1.4961
1.3172
1.1383
0.959
-0.1000 3.9192 7.9385 11.958 15.977 [s] 19.996
2nd (A) 5.5MW: Speed in p.u.
2nd (B) 5.5 MW: Speed in p.u.
197.98
118.79
39.594
-39.598
-118.79
-197.98
-0.1000 3.9192 7.9385 11.958 15.977 [s] 19.996
2nd (A) 5.5MW: Rotor angle with reference to reference machine angle in deg
2nd (B) 5.5 MW: Rotor angle with reference to reference machine angle in deg
DIgSILENT
1.6026
1.2669
0.931
0.595
0.259
-0.0763
-0.1000 3.9192 7.9385 11.958 15.977 [s] 19.996
2nd (A) 5.5MW: Excitation Voltage in p.u.
2nd (B) 5.5 MW: Excitation Voltage in p.u.
0.697
0.697
0.697
0.697
0.697
0.696
-0.1000 3.9192 7.9385 11.958 15.977 [s] 19.996
2nd (A) 5.5MW: Turbine Power in p.u.
2nd (B) 5.5 MW: Turbine Power in p.u.
UCT
Three phase fault dt=262msec at 2nd falls 11kV bus (no Governor)
Second falls
Date: 4/3/2002
Annex: C /4

APPENDIX D

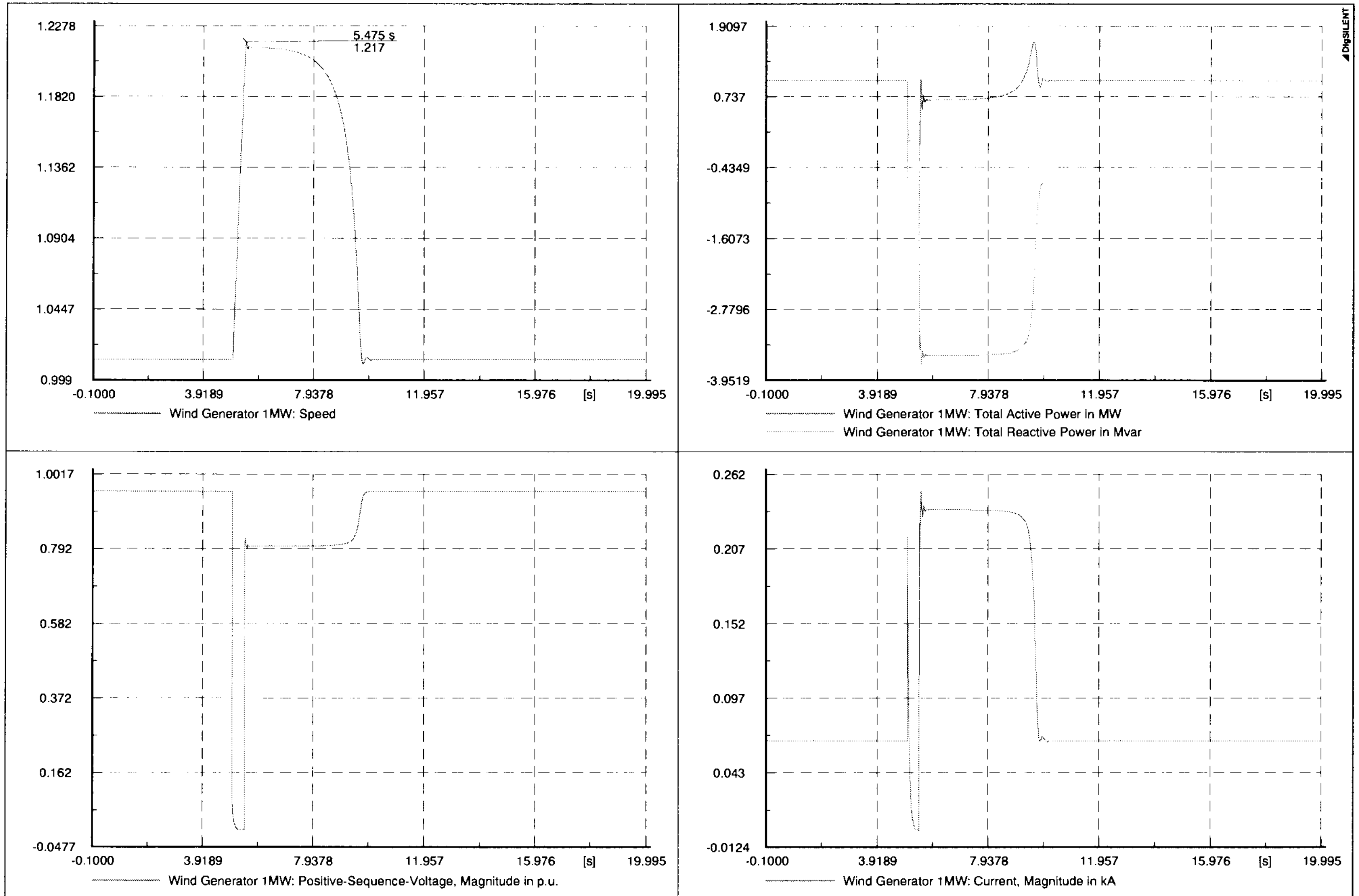
ELECTRICAL DATA FOR CASE STUDY 3 & SIMULATION RESULTS

Induction Generator

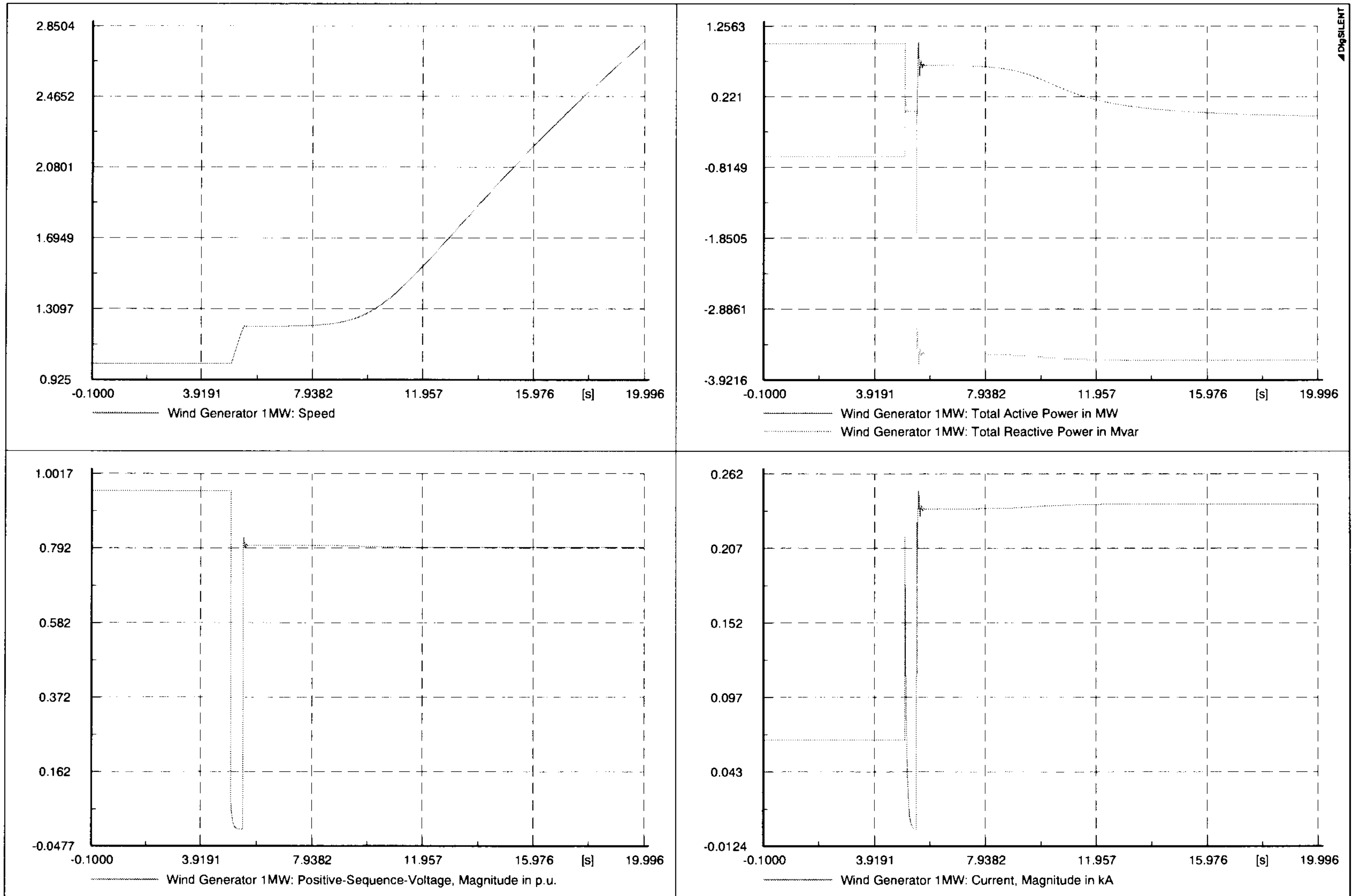
Rated Voltage	11kV
Rated MW	1MW
No of pole pairs	1
Connection	D
Rotor	Single Cage
Stator resistance [Rs]	0.01
Mag. Reactance [Xm]	2.48 p.u.
Stator Reactance [Xs]	0.098 p.u.
Rotor Resistance [R_{rA}]	0.012 p.u.
Rotor Reactance [X_{rA}]	0.12 p.u.
Acc. Time constant	2 secs



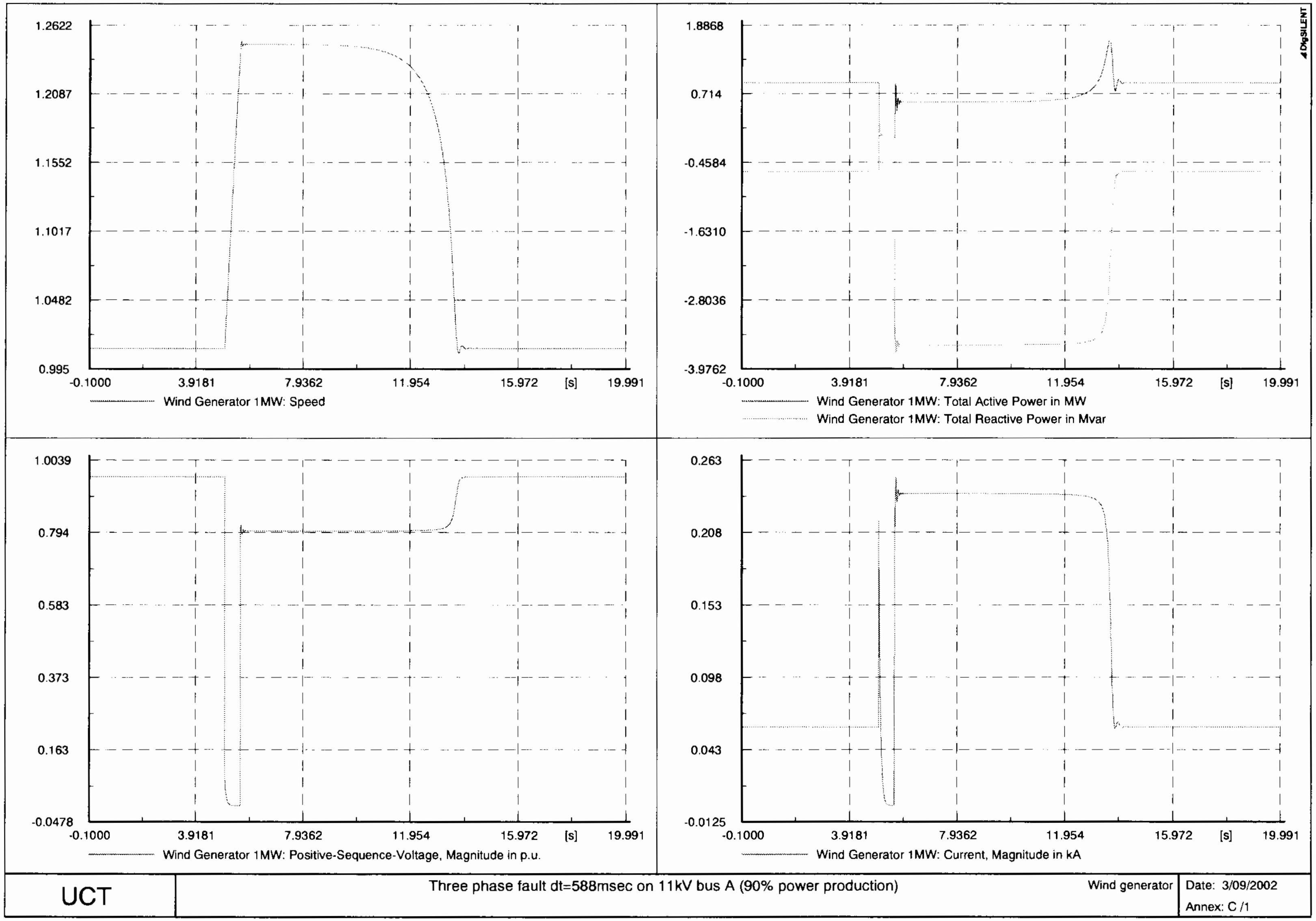
UCT Power Group	Stability of Distributed Generation	Project: DG
	Case Study 3 Typical Southern African Distribution network	Graphic: Network 1
		Date: 3/09/2001
PowerFactory 12.1.166		Annex: D



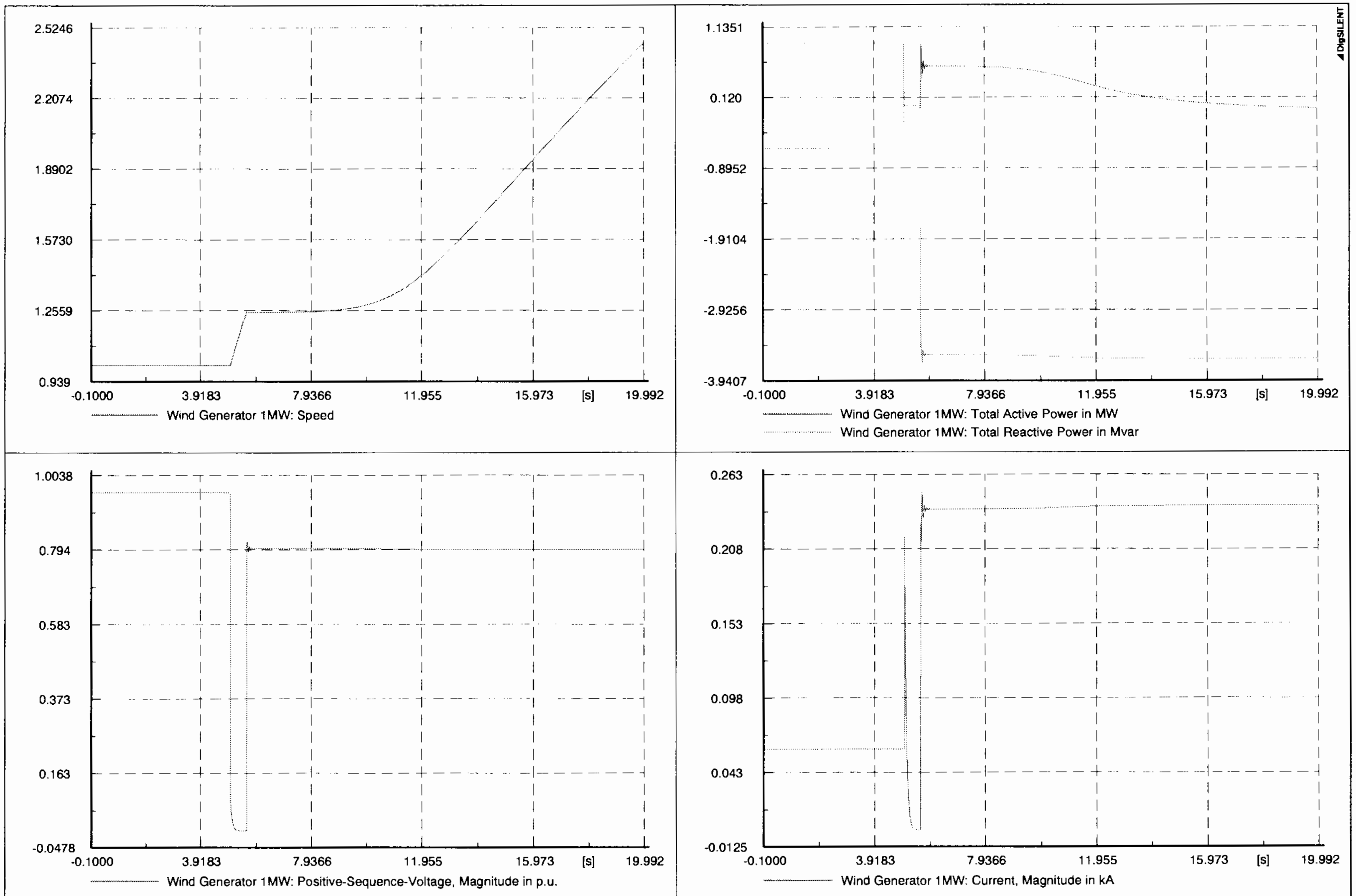
UCT	Three phase fault dt=442msec on 11kV bus A (100% power production)	Wind generator	Date: 3/09/2002 Annex: C /1



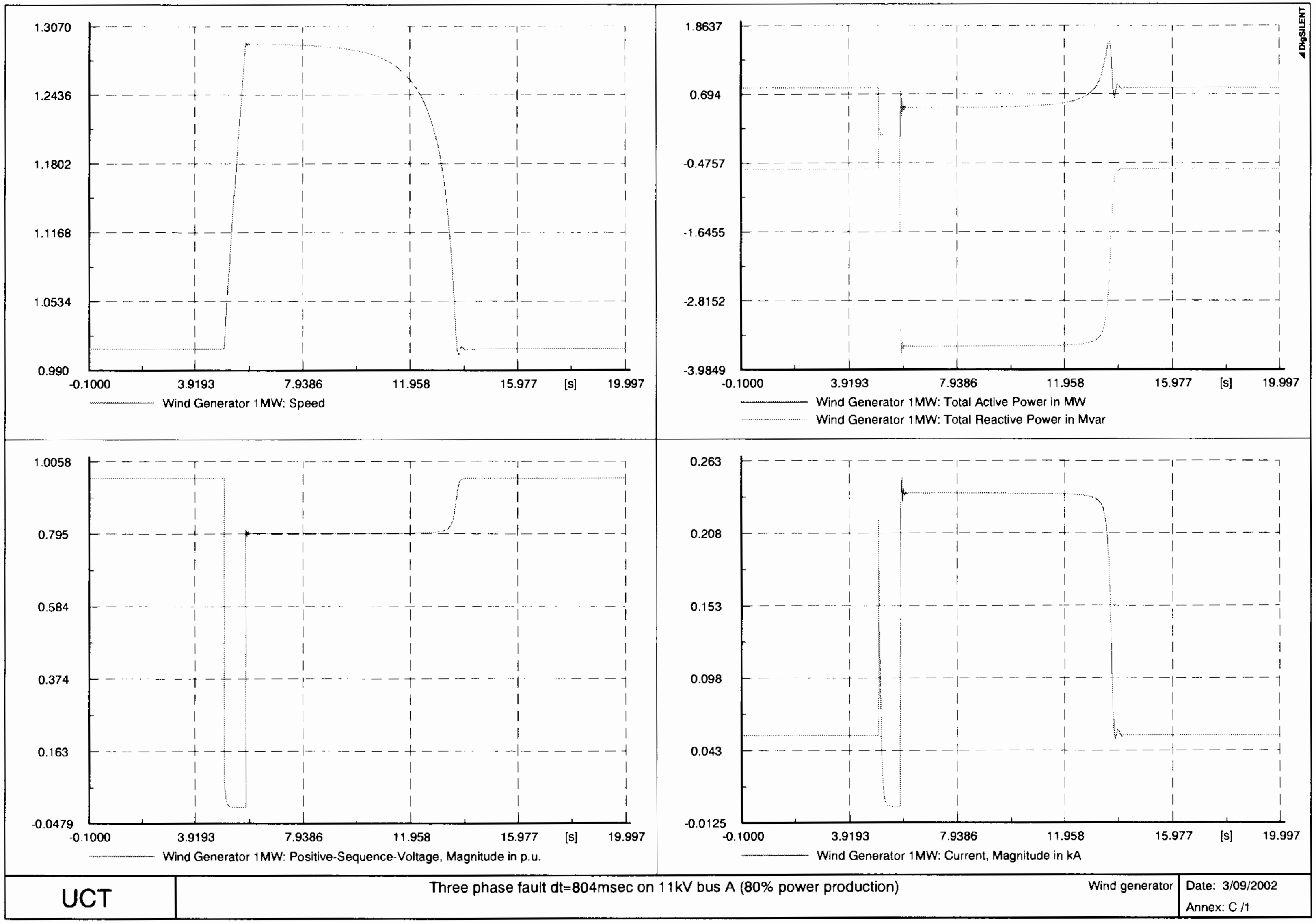
UCT	Three phase fault dt=443msec on 11kV bus A (100% power production)	Wind generator	Date: 3/09/2002 Annex: C /1

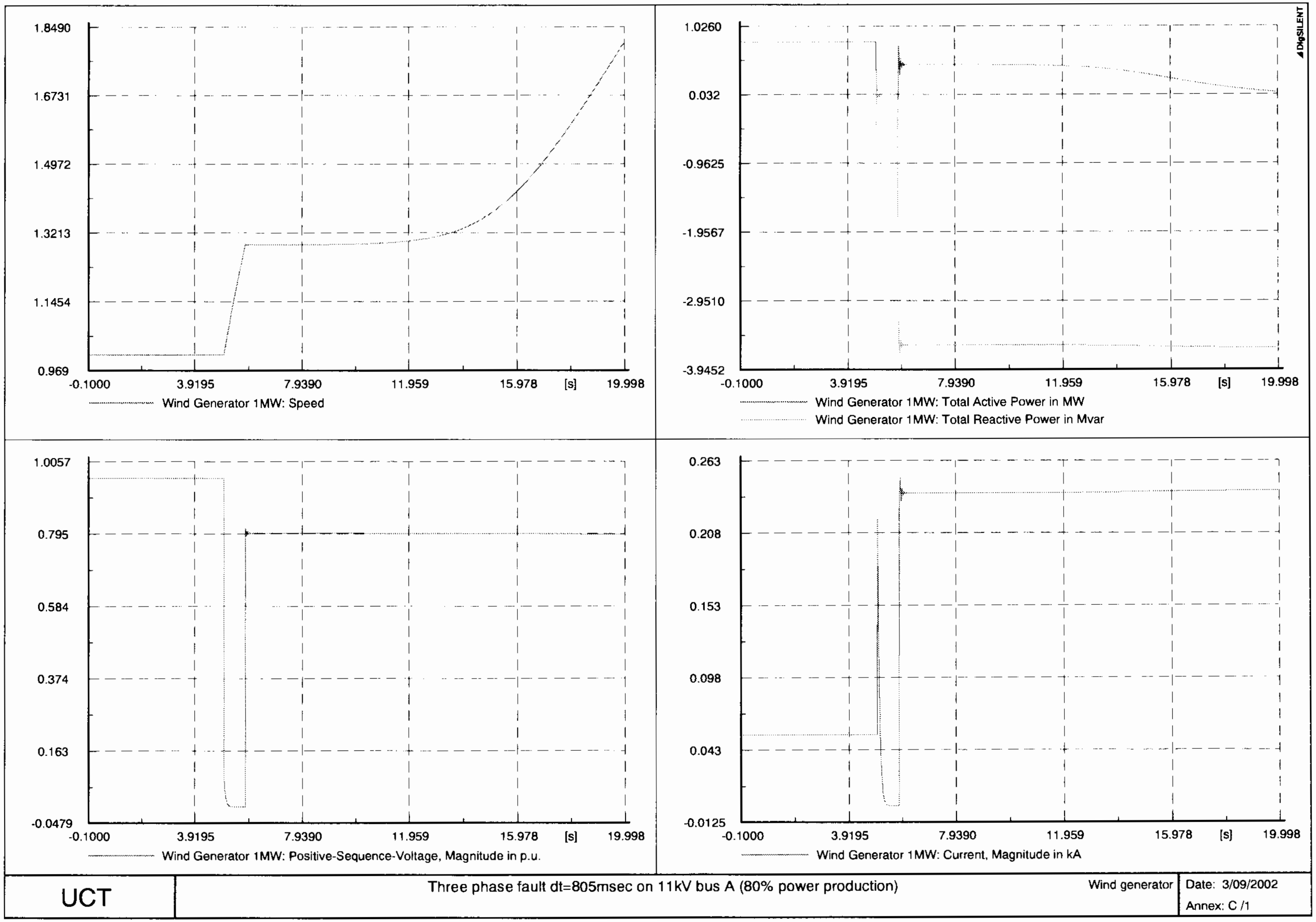


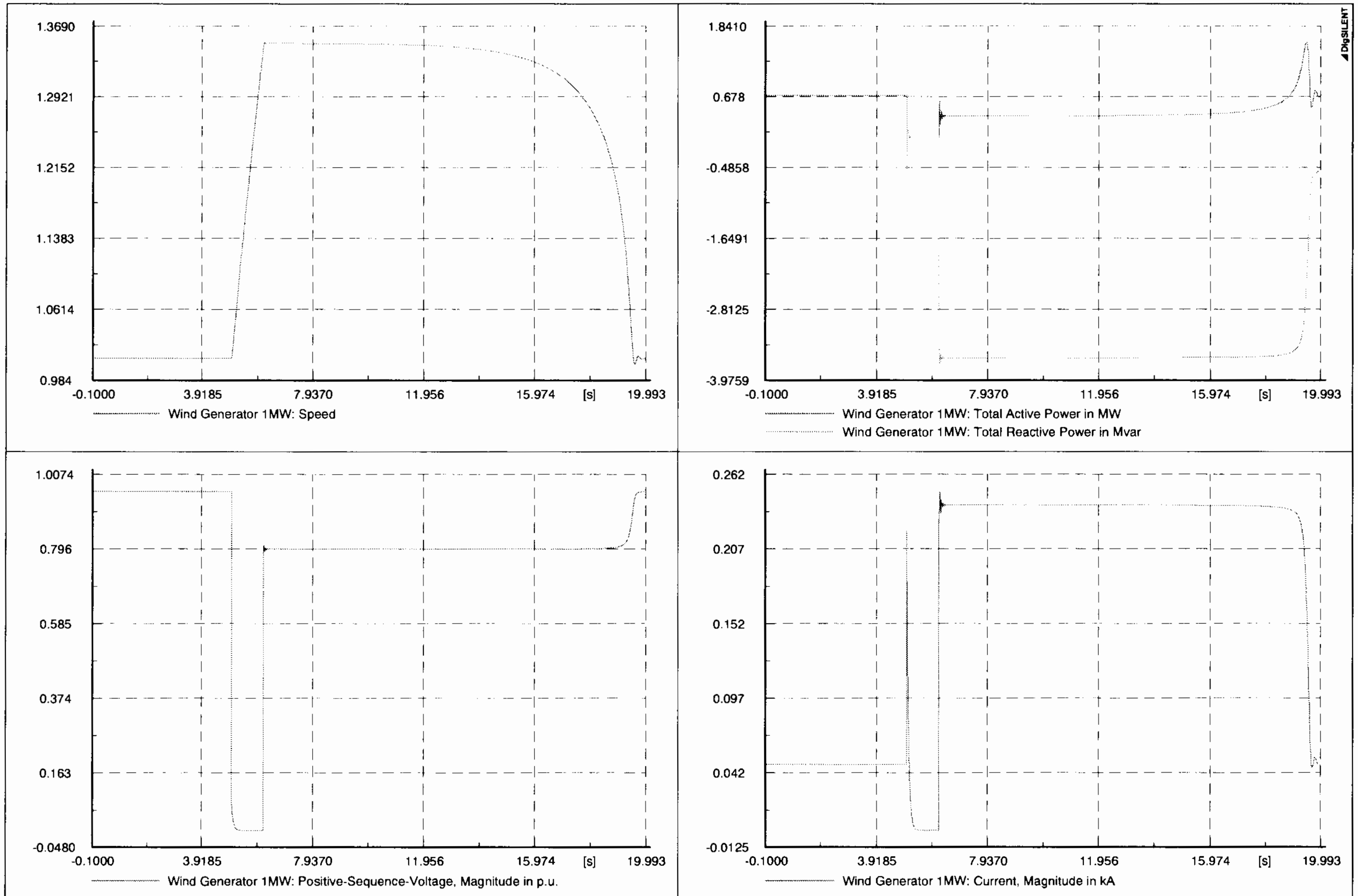
1.2622
1.2087
1.1552
1.1017
1.0482
0.995
-0.1000
3.9181
7.9362
11.954
15.972
[s]
19.991
Wind Generator 1MW: Speed
1.8868
0.714
-0.4584
-1.6310
-2.8036
-3.9762
Wind Generator 1MW: Total Active Power in MW
Wind Generator 1MW: Total Reactive Power in Mvar
DIgSILENT
1.0039
0.794
0.583
0.373
0.163
-0.0478
Wind Generator 1MW: Positive-Sequence-Voltage, Magnitude in p.u.
0.263
0.208
0.153
0.098
0.043
-0.0125
Wind Generator 1MW: Current, Magnitude in kA
UCT
Three phase fault dt=588msec on 11kV bus A (90% power production)
Wind generator
Date: 3/09/2002
Annex: C /1



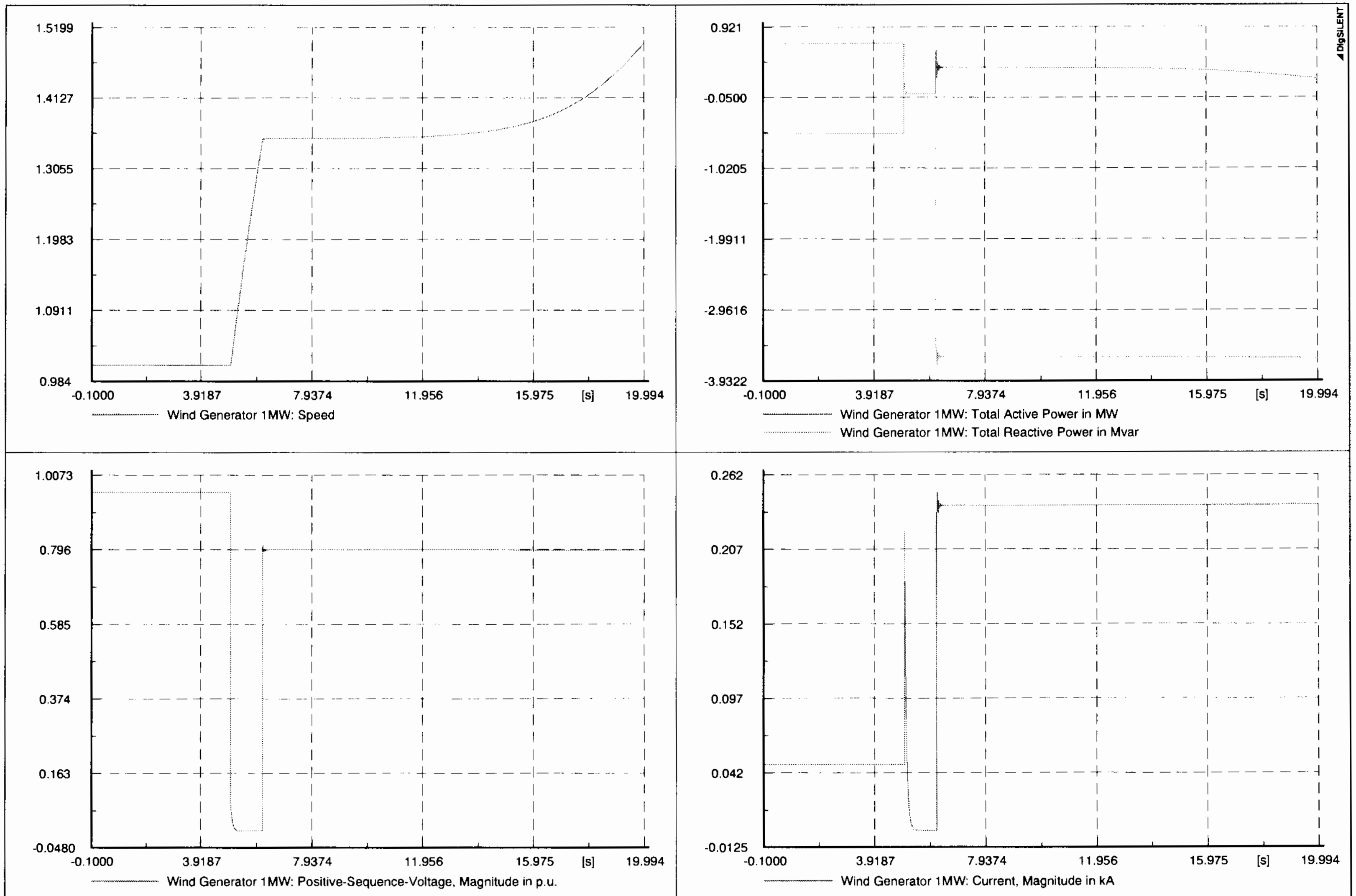
UCT	Three phase fault dt=589msec on 11kV bus A (90% power production)	Wind generator	Date: 3/09/2002 Annex: C /1


1.3070
1.2436
1.1802
1.1168
1.0534
0.990
-0.1000
3.9193
7.9386
11.958
15.977
[s]
19.997
Wind Generator 1MW: Speed
1.8637
0.694
-0.4757
-1.6455
-2.8152
-3.9849
DIgSILENT
Wind Generator 1MW: Total Active Power in MW
Wind Generator 1MW: Total Reactive Power in Mvar
1.0058
0.795
0.584
0.374
0.163
-0.0479
Wind Generator 1MW: Positive-Sequence-Voltage, Magnitude in p.u.
0.263
0.208
0.153
0.098
0.043
-0.0125
Wind Generator 1MW: Current, Magnitude in kA
UCT
Three phase fault dt=804msec on 11kV bus A (80% power production)
Wind generator
Date: 3/09/2002
Annex: C /1

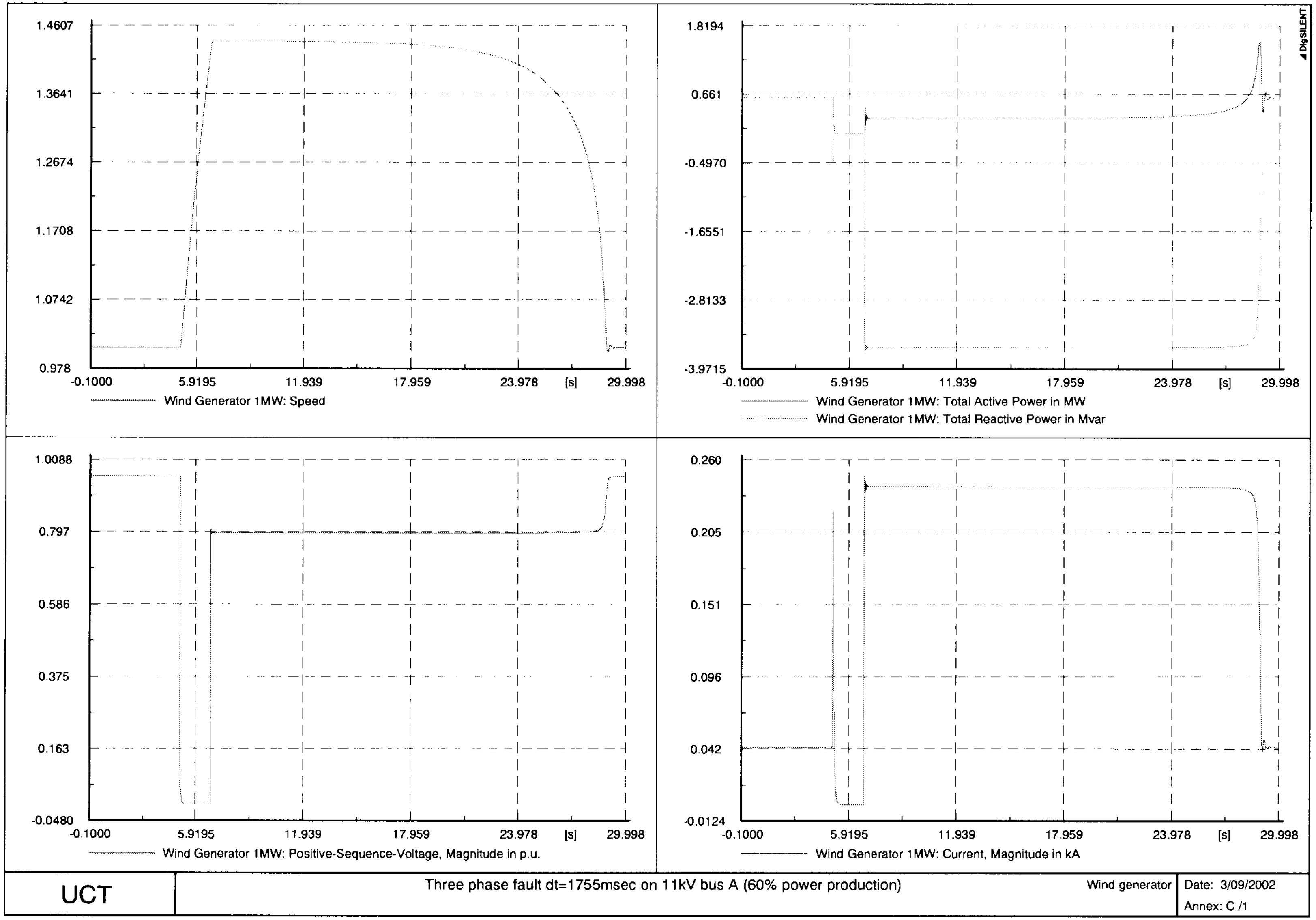

1.8490
1.6731
1.4972
1.3213
1.1454
0.969
-0.1000
3.9195
7.9390
11.959
15.978
[s]
19.998
Wind Generator 1MW: Speed
1.0260
0.032
-0.9625
-1.9567
-2.9510
-3.9452
Wind Generator 1MW: Total Active Power in MW
Wind Generator 1MW: Total Reactive Power in Mvar
DIgSILENT
1.0057
0.795
0.584
0.374
0.163
-0.0479
Wind Generator 1MW: Positive-Sequence-Voltage, Magnitude in p.u.
0.263
0.208
0.153
0.098
0.043
-0.0125
Wind Generator 1MW: Current, Magnitude in kA
UCT
Three phase fault dt=805msec on 11kV bus A (80% power production)
Wind generator
Date: 3/09/2002
Annex: C /1

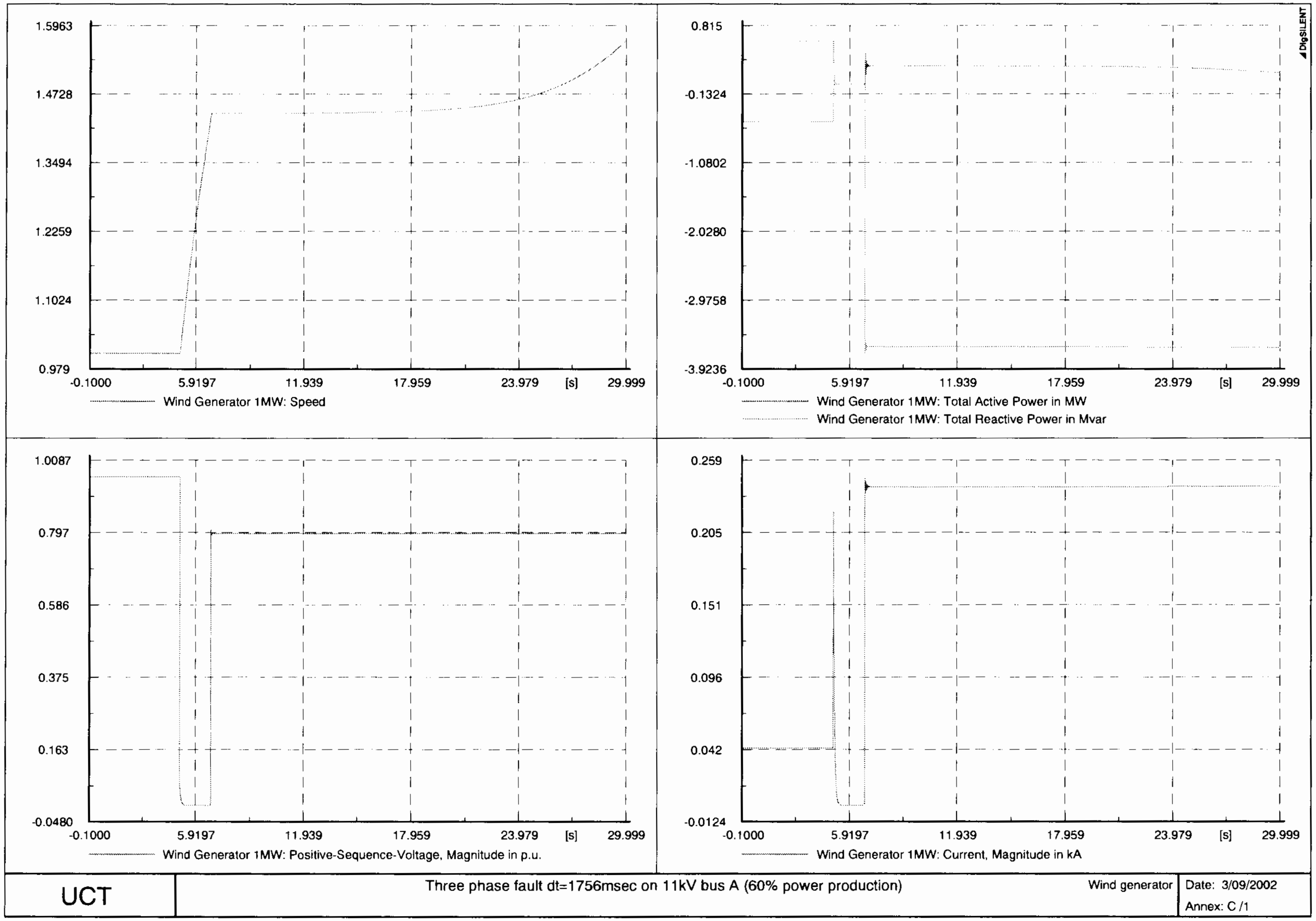


UCT	Three phase fault dt=1150msec on 11kV bus A (70% power production)	Wind generator	Date: 3/09/2002 Annex: C /1

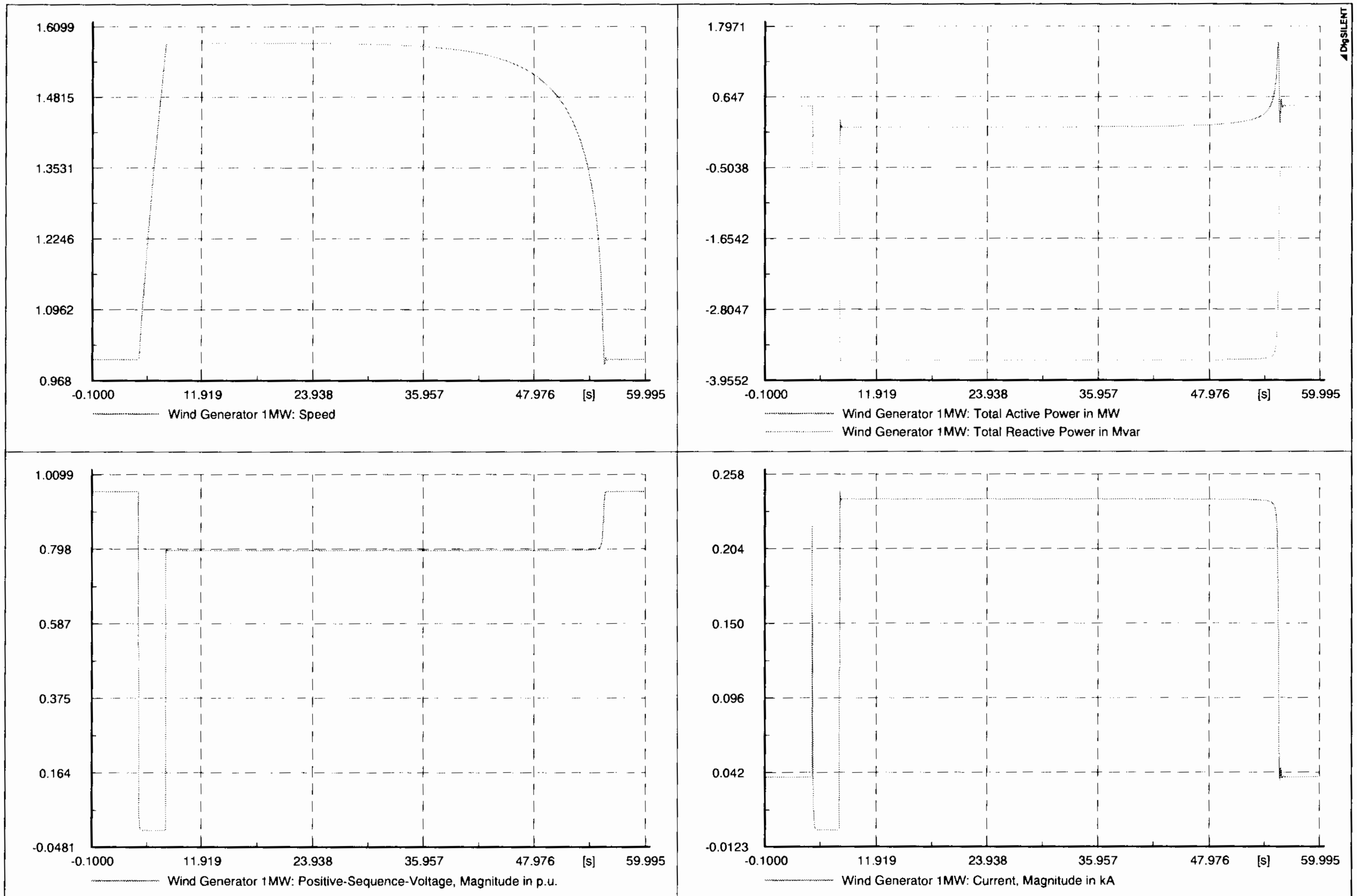


UCT	Three phase fault dt=1151msec on 11kV bus A (70% power production)	Wind generator	Date: 3/09/2002 Annex: C /1

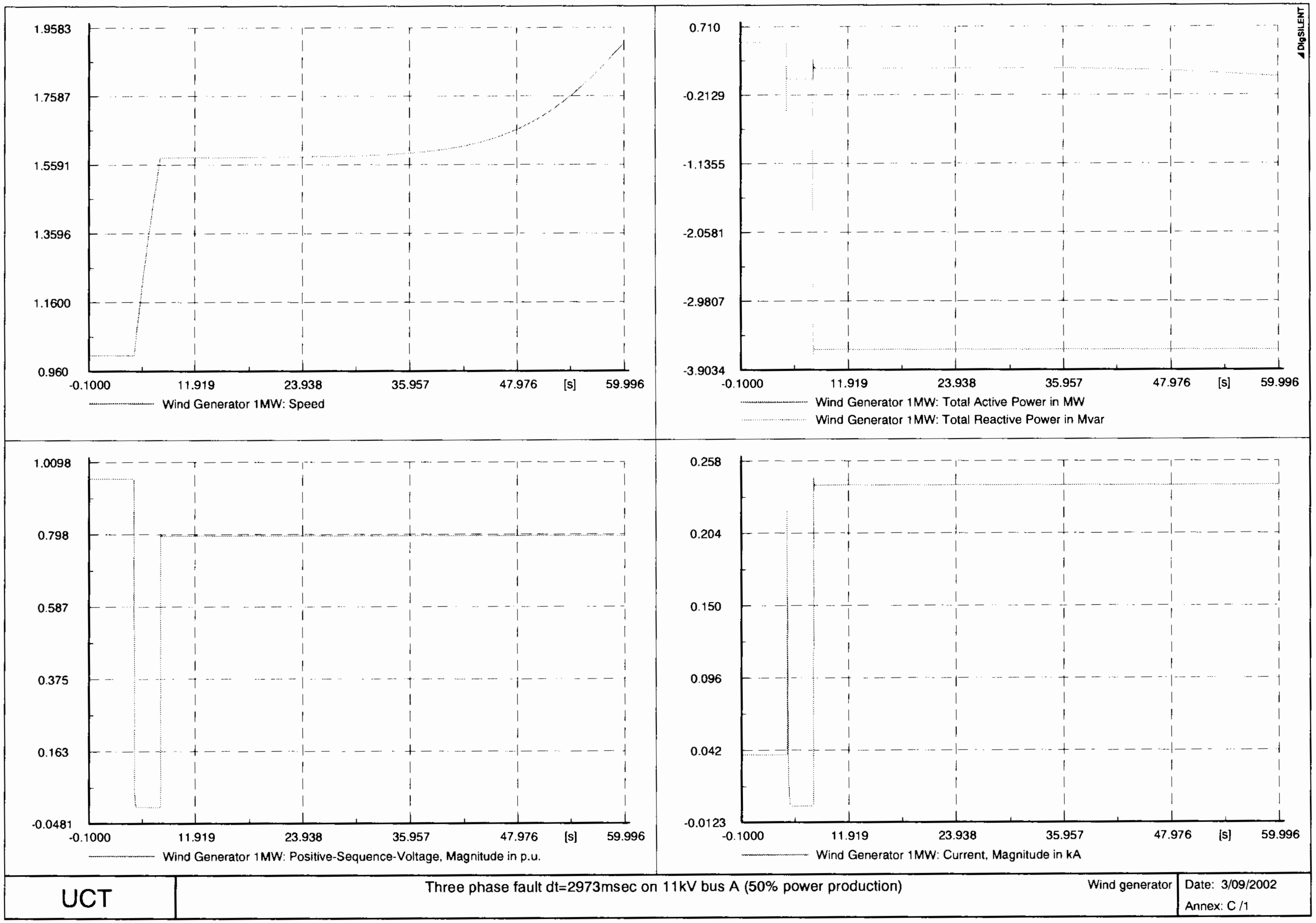

1.4607
1.3641
1.2674
1.1708
1.0742
0.978
-0.1000
5.9195
11.939
17.959
23.978
[s]
29.998
Wind Generator 1MW: Speed
1.8194
0.661
-0.4970
-1.6551
-2.8133
-3.9715
Wind Generator 1MW: Total Active Power in MW
Wind Generator 1MW: Total Reactive Power in Mvar
DIgSILENT
1.0088
0.797
0.586
0.375
0.163
-0.0480
Wind Generator 1MW: Positive-Sequence-Voltage, Magnitude in p.u.
0.260
0.205
0.151
0.096
0.042
-0.0124
Wind Generator 1MW: Current, Magnitude in kA
UCT
Three phase fault dt=1755msec on 11kV bus A (60% power production)
Wind generator
Date: 3/09/2002
Annex: C /1



1.5963
1.4728
1.3494
1.2259
1.1024
0.979
-0.1000
5.9197
11.939
17.959
23.979
[s]
29.999
Wind Generator 1MW: Speed
DIgSILENT
0.815
-0.1324
-1.0802
-2.0280
-2.9758
-3.9236
Wind Generator 1MW: Total Active Power in MW
Wind Generator 1MW: Total Reactive Power in Mvar
1.0087
0.797
0.586
0.375
0.163
-0.0480
Wind Generator 1MW: Positive-Sequence-Voltage, Magnitude in p.u.
0.259
0.205
0.151
0.096
0.042
-0.0124
Wind Generator 1MW: Current, Magnitude in kA
UCT
Three phase fault dt=1756msec on 11kV bus A (60% power production)
Wind generator
Date: 3/09/2002
Annex: C /1



UCT	Three phase fault dt=2972msec on 11kV bus A (50% power production)	Wind generator	Date: 3/09/2002 Annex: C /1



1.9583
1.7587
1.5591
1.3596
1.1600
0.960
-0.1000
11.919
23.938
35.957
47.976
[s]
59.996
Wind Generator 1MW: Speed
0.710
-0.2129
-1.1355
-2.0581
-2.9807
-3.9034
Wind Generator 1MW: Total Active Power in MW
Wind Generator 1MW: Total Reactive Power in Mvar
DIgSILENT
1.0098
0.798
0.587
0.375
0.163
-0.0481
Wind Generator 1MW: Positive-Sequence-Voltage, Magnitude in p.u.
0.258
0.204
0.150
0.096
0.042
-0.0123
Wind Generator 1MW: Current, Magnitude in kA
UCT
Three phase fault dt=2973msec on 11kV bus A (50% power production)
Wind generator
Date: 3/09/2002
Annex: C /1

APPENDIX E

ELECTRICAL DATA FOR CASE STUDY 4
&
SIMULATION RESULTS

Synchronous Generator-Mbashe 14MW (3 generators)

Rated Voltage	11kV
Rated MW	1.7MW
Power factor	0.85
Connection	YN
Stator resistance [r_s]	0.0051716
Leakage Reactance [X_l]	0.1
Inertia constant, sec	2
Xd	1.2
Xq	0.9
X'd	0.355
X'q	
X"d	0.12
X"q	0.1
Td'	1.5
T'q	
T"d	0.01
T"q	0.01

Governor (synchronous machine)

Tw	1
Qnl	0
Tg	0.2
Actual turbine power coeff [At]	1
Turbine nominal power [Pturb]	0
Dturb	0
R	0.04
Tf	0.01
Tr	0.05
Gmin	0
Gmax	1
Velm	0.16

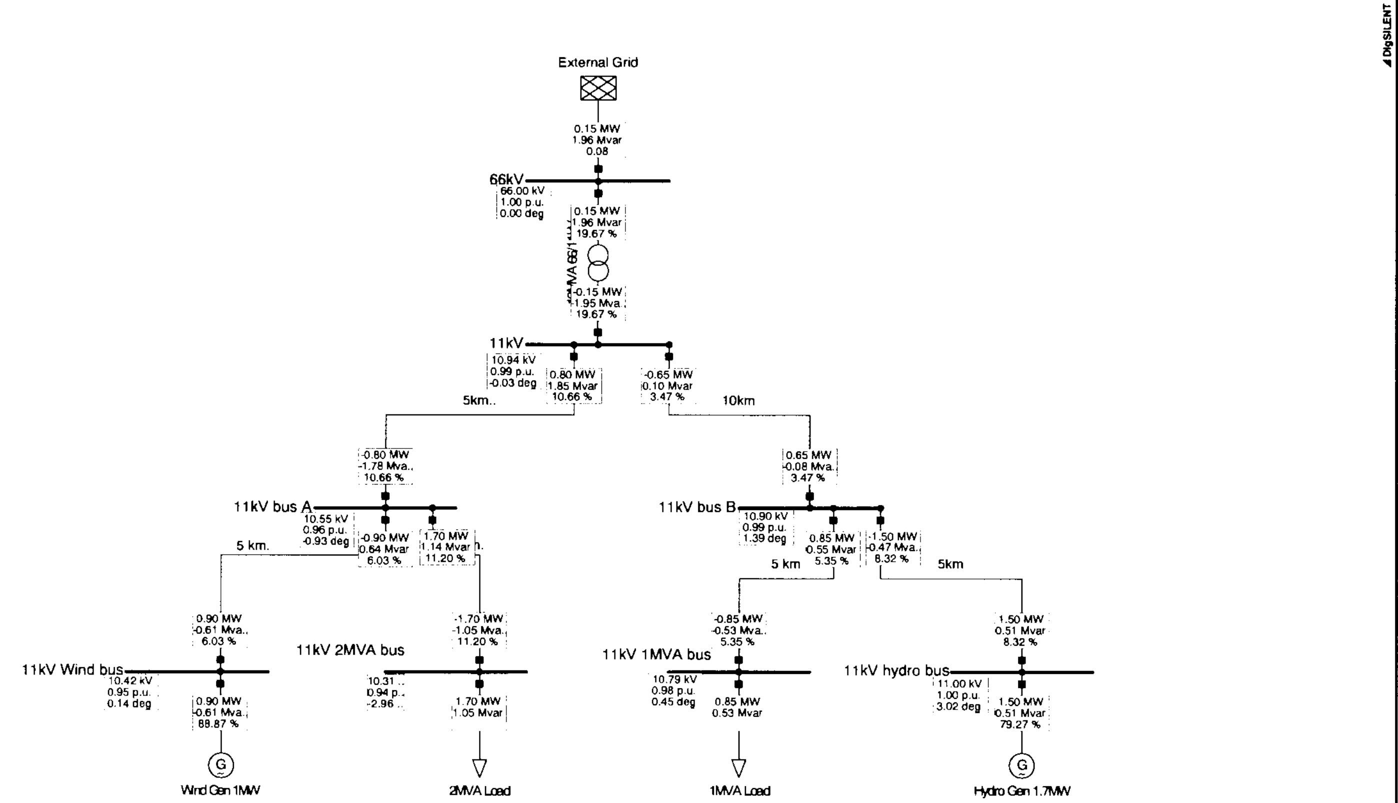
Exciter (synchronous generator)

Tr	0
Kc	0.2
Tb	10
Tc	0

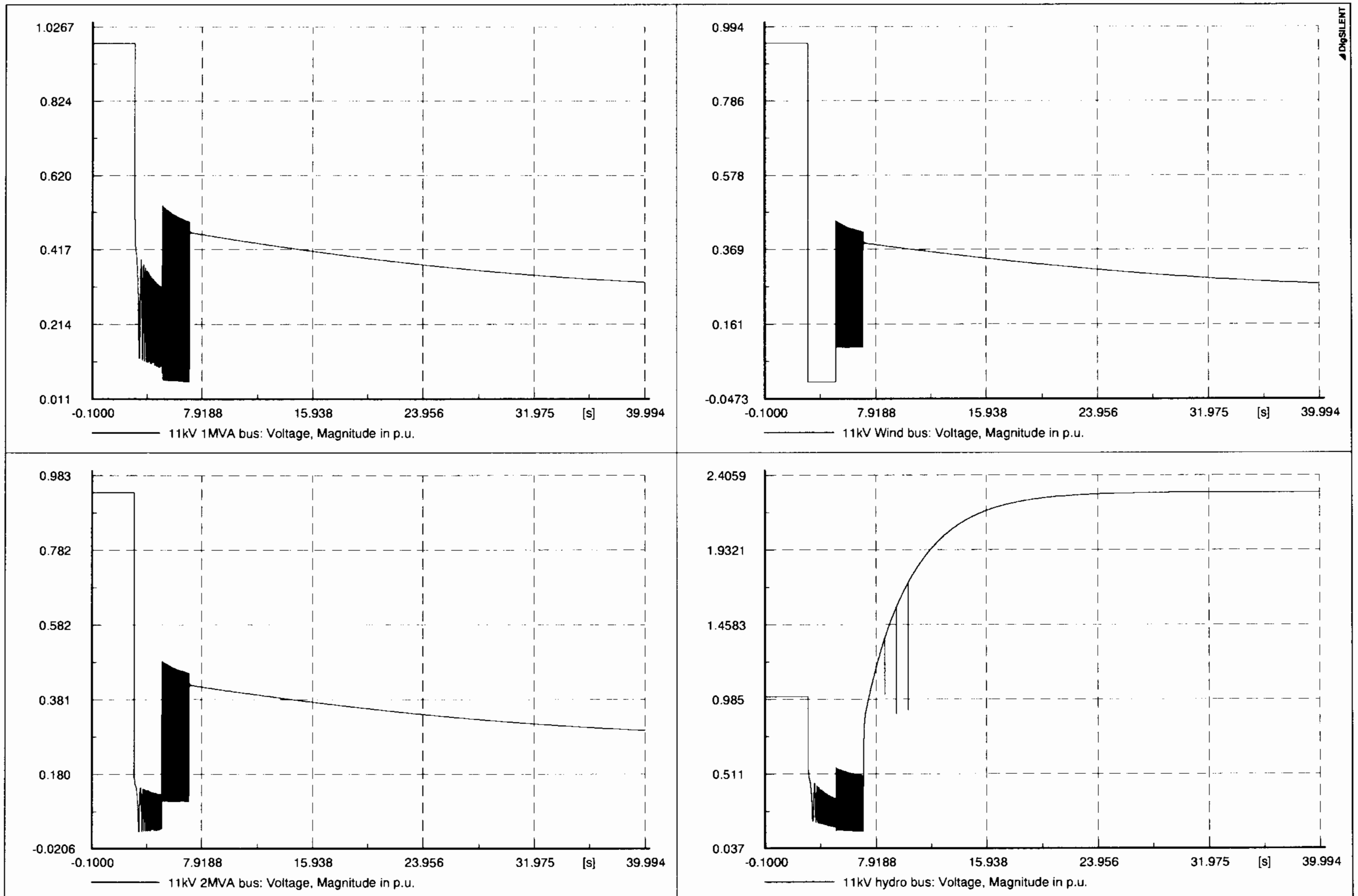
Ka	200
Ta	0.1
Te	0.05
Ke	1
E1	4.18
SE1	0.1
E2	0.03
SE2	3.14
Kd	0.38
Kf	0.03
Tf	1
Vrmin	-5.43
Vrmax	6.03

Induction Generator

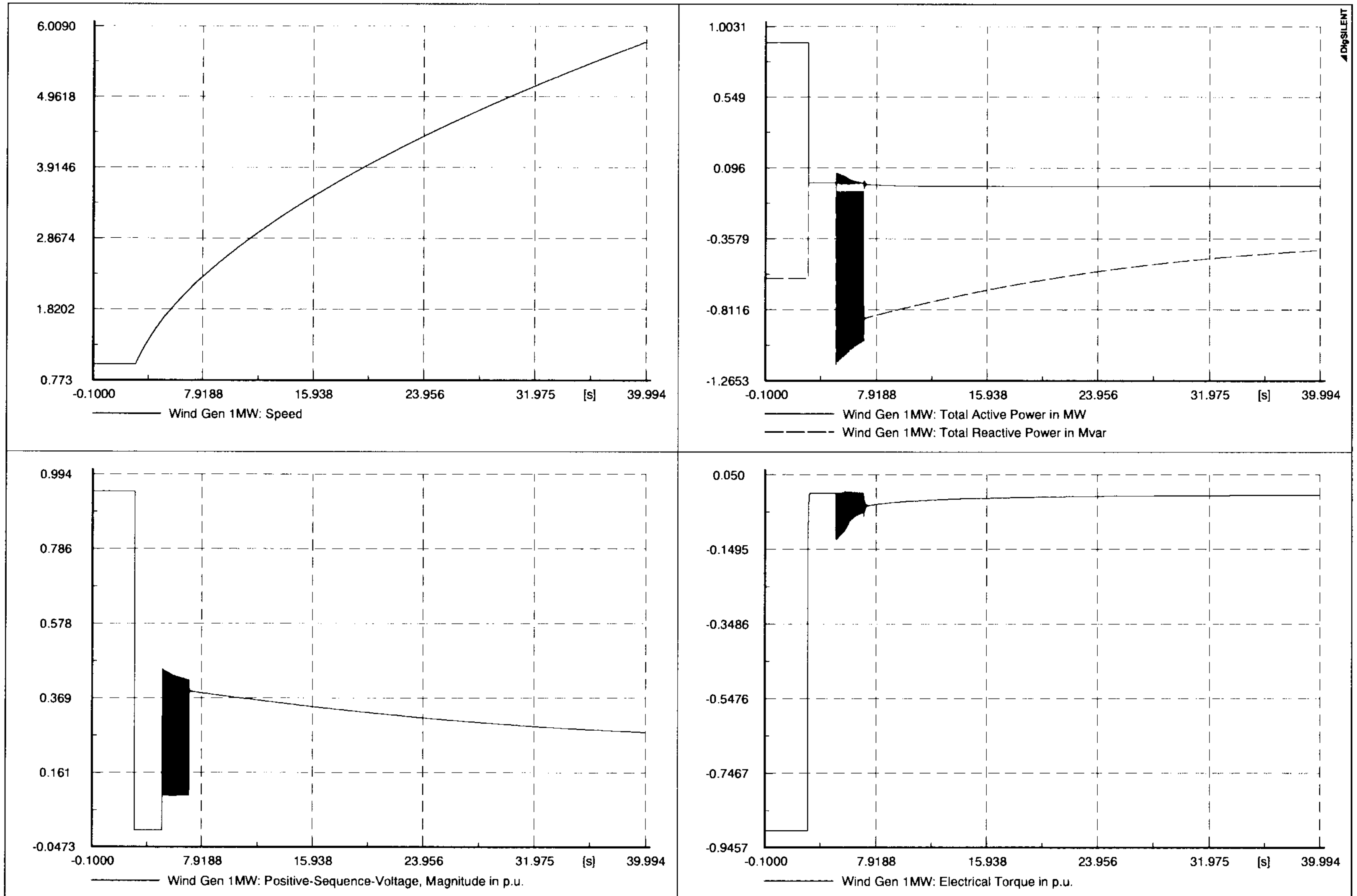
Rated Voltage	11kV
Rated MW	1MW
No of pole pairs	1
Connection	D
Rotor	Single Cage
Stator resistance [Rs]	0.01
Mag. Reactance [Xm]	2.48 p.u.
Stator Reactance [Xs]	0.098 p.u.
Rotor Resistance [R_{rA}]	0.012 p.u.
Rotor Reactance [X_{rA}]	0.12 p.u.
Acc. Time constant	2 secs



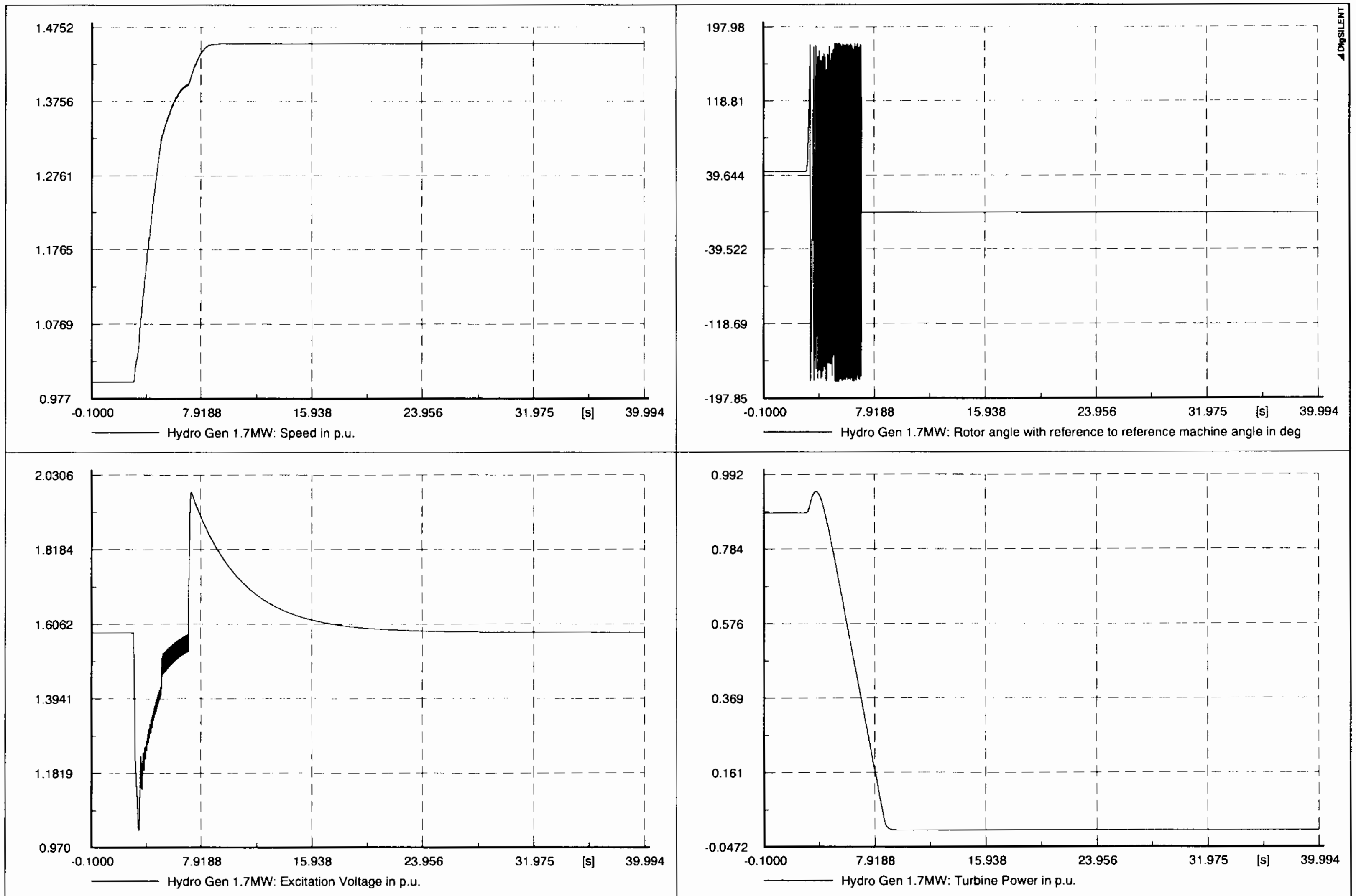
UCT Sicelo	Stability of Distributed Generation	Project: Stability
	Case Study 4 Voltage Instability on Weak distribution network	Graphic: Network cs5
		Date: 4/13/02
PowerFactory 12.1.166		Annex: E



UCT	Three phase fault dt=2secs at 3 seconds, hydro disconnected at 7 seconds	INDUCTION GEN BUS	Date: 4/14/02 Annex: E /1



UCT	Three phase fault dt=2secs at 3 seconds, hydro disconnected at 7 seconds	INDUCTION GEN	Date: 4/14/02 Annex: E /2



UCT	Three phase fault dt=2secs at 3 seconds, hydro disconnected at 7 seconds	Hydro generator	Date: 4/14/02 Annex: E /3

APPENDIX F

TRANSKEI SAMPLE PHOTOGRAPHS

1ST Falls hydro generator

1st Falls hydro turbine

1st Falls power station

1st Falls main inlet valve (MIV)

2nd Falls hydro generator

2nd Falls power station

Mbashe dam wall

Mbashe control room

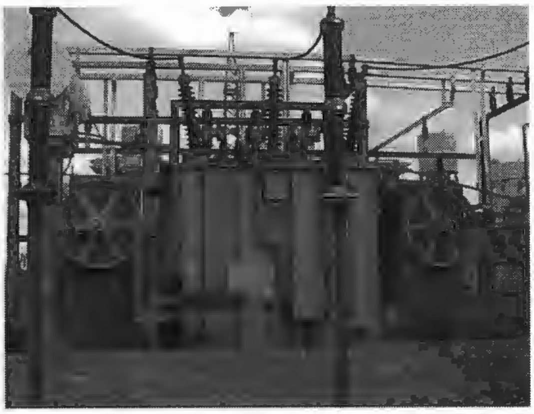
Mbashe Hydro station

Mbashe hydro generator

Mbashe hydro station

SVC at Zimbane substation

SVC inductance at Zimbane substation



SVC Transformer at Zimbane substation

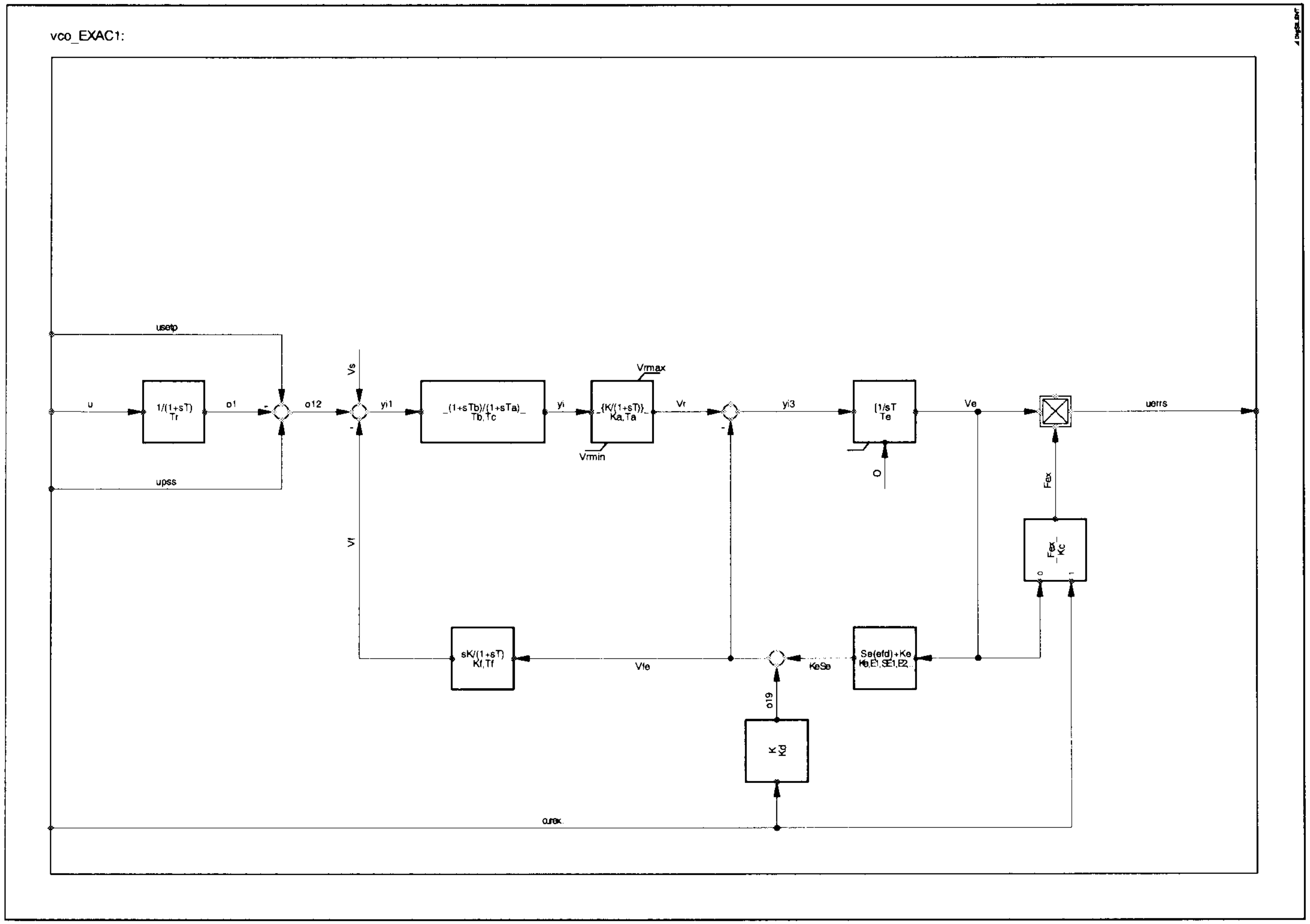
Zimbane 132kV sub station

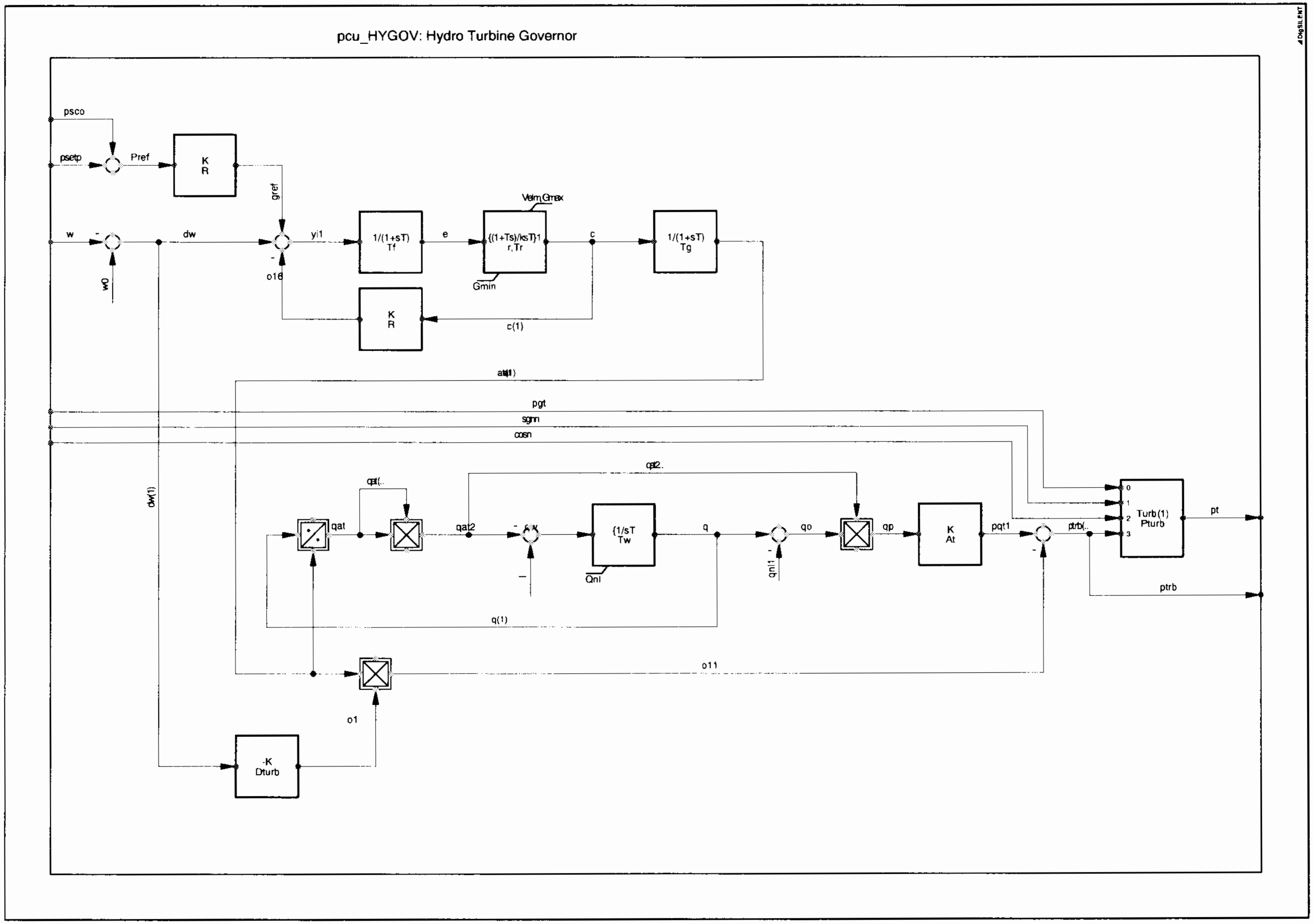
Mbashe hydro sub station

1st Falls hydro sub station

Umtata dam wall

APPENDIX G
AVR & GOVERNOR MODELS




pcu_HYGOV: Hydro Turbine Governor
psco
psetp
Pref
K
R
gref
w
dw
w0
yi1
o16
1/(1+sT)
Tf
e
{(1+Ts)/ksT}1
r,Tr
Velm,Gmax
Gmin
c
c(1)
1/(1+sT)
Tg
pgt
sgnn
cosn
qat
qat2
q
q(1)
{1/sT
Tw
Qnl
qnl1
qo
qp
At
pqt1
ptrb
Turb(1)
Pturb
pt
o11
o1
-K
Dturb
dw(1)

APPENDIX H

PHYSICAL AND ELECTRICAL DATA FOR ACSR SIZES

Code Name	Equival. Copper Area (mm^2)	Stranding/ Wire diam. (mm)	Overall Diam.	Aluminium (kg/km)	Steel (k/km)	Total (kg/km)	Ultimate tensile stregth (N)	DC Resist. At 20°C (ohms/km)	Current rating (amps)
hare	64,52	6/1/4,72	14,16	289	138	427	36000	0,2733	360
Wolf	96,77	30/7/2,59	18,13	438	292	730	69200	0,1828	470
rabbit	32,26	6/1/3,35	10,05	145	69,40	214	18500	0,5426	240
mink	38,71	6/1/3,66	10,89	174	82,80	257	21900	0,4546	260